AMERICAN JOURNAL OF PREVENTIVE MEDICINE

A forum for the communication of information, knowledge, and wisdom in prevention science, education, practice, and policy.

A Journal of the ACPM American College of Preventive Medicine & APTR ASSOCIATION FOR PREVENTION TEACHING AND RESEARCH

Published by **Elsevier Inc**
AJPM-ONLINE.NET

Editorial correspondence should be directed to:

Editor
American Journal of Preventive Medicine
University of California, San Diego
9500 Gilman Drive, DEPT 0811
La Jolla CA 92093-0811

E-mail for AJPM business:
ajpm@ucsd.edu
E-mail for manuscript queries:
eAJPM@ucsd.edu
E-mail for press queries:
PRajpm@ucsd.edu

Tel (858)457-7292
Fax (858)622-1463

AJPM Online:
www.ajpm-online.net
Fed Ex Address:
8950 Villa La Jolla Drive B-122
La Jolla CA 92037

Sponsoring Organizations' Offices:

American College of Preventive Medicine
Michael A. Barry
Executive Director
1307 New York Avenue, NW,
Suite 200
Washington DC 20005
Tel (202) 466-2044
Fax (202) 466-2662
www.acpm.org

Association for Prevention Teaching and Research
Allison L. Lewis
Executive Director
1001 Connecticut Avenue, NW,
Suite 610
Washington DC 20036
Tel (202) 463-0550
Fax (202) 463-0555
www.aptrweb.org

Author's Instructions on AJPM's Website

Complete author's instructions and guidelines for submitting manuscripts to the **American Journal of Preventive Medicine** can be found in each January issue and on the **AJPM Online Website:** www.ajpm-online.net. The Journal welcomes brief reports (max. 1200 words); research articles (3000 words); RCTs/community-based trials (4000 words); and review articles (4000 words) on all aspects of practice, education, policy, and research in preventive medicine and public health.

The American Journal of Preventive Medicine is indexed and abstracted in Index Medicus/MEDLINE, EMBASE/Excerpta Medica, MEDLARS, Psychological Abstracts, PsycINFO, Sociological Abstracts, the Health Promotion and Education and the Cancer Prevention and Control Databases of CHID on BRS, the Smoking and Health Database on DIALOG, and Science Citation Index, Research Alert, and Current Contents.

∞ The journal is printed on acid-free paper that meets the minimum requirements of ANSI Standard Z39.48-1984 (Permanence of Paper), beginning with volume 1, number 1.

AMERICAN JOURNAL OF
PREVENTIVE MEDICINE

VOLUME 35(2S) AUGUST 2008 AJPM-ONLINE.NET

[Contents continued on next page]

A Journal of the
ACPM
American College of Preventive Medicine
&
ATPM
Association of Teachers of Preventive Medicine

ELSEVIER
ISSN 0749-3797

[Contents continued from previous page]

Acknowledgments

This supplement addresses new developments in the emerging *science of team science*—a field of evaluation research concerned especially with understanding and enhancing the outcomes of collaborative research and training programs.

The articles in this issue are drawn from the proceedings of the National Cancer Institute (NCI)-National Institutes of Health (NIH) Conference on the Science of Team Science held in Bethesda, Maryland, during October 2006. The agenda for that conference was developed during the preceding year following the NCI Transdisciplinary Conference Planning Team Meeting in Bethesda MD held during October 2005. Both of these conferences and the present supplement were sponsored and funded by the Division of Cancer Control and Population Sciences (DCCPS) within NCI, directed by Dr. Robert Croyle.

The Guest Editors gratefully acknowledge Dr. Croyle's visionary leadership of DCCPS in helping to establish a vibrant science of team science program within NCI, NIH, and beyond.

We also thank the many colleagues within DCCPS at NCI who supported our efforts to organize the 2005 and 2006 conferences in Bethesda, and the members of the NCI Transdisciplinary Conference Planning Team who helped formulate the agendas for both meetings.

As well, we appreciate the conscientious efforts of colleagues who contributed articles for this supplement and those of the external reviewers who offered valuable suggestions for improving the articles published in this issue.

Finally, we are grateful to the AJPM staff for their encouragement to develop the supplement and their patience and assistance throughout the many stages of editing and producing this special issue.

The Science of Team Science

Overview of the Field and Introduction to the Supplement

Daniel Stokols, PhD, Kara L. Hall, PhD, Brandie K. Taylor, MA, Richard P. Moser, PhD

Abstract: The science of team science encompasses an amalgam of conceptual and methodologic strategies aimed at understanding and enhancing the outcomes of large-scale collaborative research and training programs. This field has emerged rapidly in recent years, largely in response to growing concerns about the cost effectiveness of public- and private-sector investments in team-based science and training initiatives. The distinctive boundaries and substantive concerns of this field, however, have remained difficult to discern. An important challenge for the field is to characterize the science of team science more clearly in terms of its major theoretical, methodologic, and translational concerns. The articles in this supplement address this challenge, especially in the context of designing, implementing, and evaluating cross-disciplinary research initiatives. This introductory article summarizes the major goals and organizing themes of the supplement, draws links between the constituent articles, and identifies new areas of study within the science of team science.
(Am J Prev Med 2008;35(2S):S77–S89) © 2008 American Journal of Preventive Medicine

Background

The past two decades have witnessed a surge of interest and investments in large-scale team science programs.[1–7] Ambitious multiyear initiatives to promote cross-disciplinary collaboration in research and training have been launched by several public agencies and private foundations.[8–15] Considering the enormous complexity and multifactorial causation of the most vexing social, environmental, and public health problems (e.g., terrorism and inter-ethnic violence; global warming; cancer, heart disease, diabetes, and AIDS; health disparities among minority populations), efforts to foster greater collaboration among scientists trained in different fields are not only a useful but also an essential strategy for ameliorating these problems.[16–22] At the same time, some observers of science policy question whether the current popularity of cross-disciplinary research and training is merely a passing fad whose scientific and societal value, relative to smaller-scale unidisciplinary projects, has been overstated.[23] Critics of cross-disciplinary initiatives contend that they divert valuable resources from important discipline-based research and draw scientists into collaborative centers and teams who otherwise might be more productive working independently or as co-investigators on smaller-scale projects.[24,25]

As public and private investments in team science initiatives have grown and debates about their intellectual and societal value have ensued, the importance of clearly defining and evaluating the effectiveness of these programs has become more evident.[26–31] Practical concerns about gauging the value added and the return on investment accruing from large research initiatives[4,26,32] have given rise to **the science of team science**, a rapidly emerging yet still-amorphous field characterized by a lack of consensus about its defining substantive boundaries and core concerns.

The goals of this article are twofold: (1) to describe the science of team science in terms of its major conceptual, methodologic, and translational concerns; and (2) to introduce the present supplement to the *American Journal of Preventive Medicine* on the science of team science by offering an overview of its organization and specific aims.[9,19,27,33–49]

The Science of Team Science: Units of Analysis and Distinguishing Features

It is important to distinguish between team science initiatives themselves and the science-of-team-science field, whose principal units of analysis are the large research and training initiatives implemented by public agencies and nonpublic organizations and the various projects within each initiative conducted by scholars who work within and across their respective fields. Team science initiatives are designed to promote collaborative—and often cross-disciplinary—approaches to analyzing re-

From the School of Social Ecology, University of California Irvine (Stokols), Irvine, California; the Division of Cancer Control and Population Sciences, National Cancer Institute (Hall, Moser); and the Office of Portfolio Analysis and Strategic Initiatives, NIH (Taylor), Bethesda, Maryland

Address correspondence and reprint requests to: Daniel Stokols, PhD, Department of Planning, Policy and Design, UC Irvine, 206-C Social Ecology I Building, School of Social Ecology, Irvine CA 92697. E-mail: dstokols@uci.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.002

search questions about particular phenomena (e.g., the joint influence of social, behavioral, and biogenetic factors on cancer etiology and treatment examined by Hiatt and Breen,[19] and the multilevel determinants of health disparities discussed by Holmes et al.[34] in this supplement). The science-of-team-science field, on the other hand, is a branch of science studies concerned especially with understanding and managing circumstances that facilitate or hinder the effectiveness of team science initiatives.[50–54] The field as a whole focuses not on the phenomena addressed by particular team science initiatives (e.g., cancer, heart disease, obesity, community violence, environmental degradation), but rather on understanding and enhancing the antecedent conditions, collaborative processes, and outcomes associated with team science initiatives more generally, including their scientific discoveries, educational outcomes, and translations of research findings into new clinical practices and public policies.[9,35,55] Some of the distinguishing features of team science initiatives and the unique substantive concerns of the science-of-team-science field are outlined below.

Characteristics of Scientific Initiatives and Teams

Efforts to integrate knowledge in the science-of-team-science field face considerable challenges, owing to the highly disparate units of analysis found in the earlier studies of scientific teams.[27,36,56] Research teams, for example, may consist of investigators drawn from either the same or different fields (i.e., unidisciplinary versus cross-disciplinary teams). These teams vary not only in terms of their disciplinary composition but also in terms of their size, organizational complexity, and geographic scope, ranging from a few participants working at the same site to scores of investigators dispersed across multiple geographic and organizational venues.[55,57] Furthermore, the goals of team science initiatives are quite diverse (e.g., spanning scientific discovery; training; and clinical, translational, public health, and policy-related goals), and both the quality and level of intellectual integration intended and achieved among disciplines varies from one program to the next (i.e., along a continuum ranging from unidisciplinary to multidisciplinary, interdisciplinary, and transdisciplinary integration, as described more fully below).[27,37,58–60]

Because team science initiatives differ along so many dimensions, including their size, goals, duration, organizational structure, and cross-disciplinary scope, it is important to be clear at the outset about the kinds of research and training initiatives emphasized in the present discussion. Team-based projects can include a handful of scientists working together at a single site, but the focus here is on the larger and more-complex initiatives comprising many (e.g., often between 50 and 200) investigators who work collaboratively on multiple, closely related research projects, and who may be dispersed across different departments, institutions, and geographic locations.[55] Trochim and colleagues,[6] for example, define large research initiatives as grant-funded projects solicited through specific requests for applications with an average annual expenditure of at least $5 million. The usual duration of these initiatives (e.g., NIH P50 and U54 Centers, National Cancer Institute [NCI] Specialized Programs of Research Excellence [SPOREs]) is 5 years, and they may be refunded, thus extending over one or more decades, in some cases.[61] Some especially broad-gauged initiatives, such as the NIH Roadmap and the Office of Portfolio Analysis and Strategic Initiatives (OPASI) programs, provide the organizational framework and funding source for scores of other interrelated research and training initiatives, all of which are designed to promote cross-disciplinary scientific collaboration.[11,14] Often, large research initiatives incorporate career development and training components as well as clinical translation, health promotion, and policy-related functions.[13,62–64] The articles in this supplement address the full range of scientific, training, clinical translation, community outreach, health promotion, and public-policy goals emphasized within relatively large team science initiatives of varying size and complexity.

Large initiatives also vary with respect to the collaborative orientations and disciplinary perspectives of team members. This discussion focuses on initiatives intended to promote **cross-disciplinary** rather than **unidisciplinary** collaboration.[a] Cross-disciplinary teams strive to combine and, in some cases, to integrate concepts, methods, and theories drawn from two or more fields. Three different approaches to cross-disciplinary collaboration have been described by Rosenfield.[60] **Multidisciplinarity** is a process in which scholars from disparate fields work independently or sequentially, periodically coming together to share their individual perspectives for purposes of achieving broader-gauged analyses of common research problems. Participants in multidisciplinary teams remain firmly anchored in the concepts and methods of their respective fields. **Interdisciplinarity** is a more robust approach to scientific integration in the sense that team members not only combine or juxtapose concepts and

[a]Distinctions between cross-disciplinary and unidisciplinary collaboration depend on how individual disciplines are defined and bounded.[65] Disciplines are generally organized around distinctive substantive concerns (e.g., biological, psychological, environmental, or sociologic phenomena); analytic levels (e.g., molecular, cellular, cognitive, behavioral, interpersonal, organizational, community); and concepts, methods, and measures associated with particular fields. The boundaries between disciplines and subdisciplines are to some extent arbitrarily defined and agreed upon by communities of scholars.[66,67] For instance, the boundaries between some fields may be overlapping (e.g., physiology and molecular biology) and other fields, such as public health and urban planning, are inherently multidisciplinary in that they combine several disciplinary perspectives in analyses of population health and urban development.

Table 1. Definitions and examples of scientific orientations[60]

Scientific orientation	Definition	Example
Unidisciplinarity	**Unidisciplinarity** is a process in which researchers from a **single discipline** work together to address a common research problem.	A team of pharmacologists collaborate on a laboratory study of the relationships between nicotine consumption and insulin metabolism.
Multidisciplinarity	**Multidisciplinarity** is a **sequential** process whereby researchers in different disciplines work **independently**, each from his or her own discipline-specific perspective, with a goal of eventually combining efforts to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist each contribute sections to a multi-authored manuscript that reviews research in their respective fields pertaining to the links between nicotine consumption, changes in brain chemistry and caloric intake induced by nicotine, and physical activity levels.
Interdisciplinarity	**Interdisciplinarity** is an **interactive** process in which researchers work **jointly**, each drawing from his or her own discipline-specific perspective, to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist conduct a collaborative study to examine the interrelations among patterns of nicotine consumption, brain chemistry, caloric intake, and physical activity levels. Their research design incorporates conceptual and methodologic approaches drawn from each of their respective fields.
Transdisciplinarity	**Transdisciplinarity** is an **integrative** process in which researchers work jointly to develop and use a shared conceptual framework that **synthesizes** and **extends** discipline-specific theories, concepts, methods, or all three to create **new** models and language to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist conduct a collaborative study to examine the interrelations among nicotine consumption, brain chemistry, caloric intake, and physical activity levels. Based on their findings, they develop a neurobehavioral model of the links among tobacco consumption, brain chemistry, insulin metabolism, physical activity, and obesity that integrates and extends the concepts and methods drawn from their respective fields.

methods drawn from their different fields, but also work more intensively to integrate their divergent perspectives, even while remaining anchored in their own respective fields.[27]

Transdisciplinarity is a process in which team members representing different fields work together over extended periods to develop shared conceptual and methodologic frameworks that not only integrate but also transcend their respective disciplinary perspectives.[b] Examples of unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary scientific orientations are provided in Table 1. Transdisciplinary collaborations perhaps have the greatest potential to produce highly novel and generative scientific outcomes, but they are more difficult to achieve and sustain than unidisciplinary, multidisciplinary, and interdisciplinary projects due to their greater complexity and loftier aspirations for achieving transcendent, supra-disciplinary integrations.[27,31,37,56,68–70]

The ensuing discussion focuses primarily on interdisciplinary and transdisciplinary science initiatives in which an explicit goal of the collaboration is to integrate theories, methods, and training strategies drawn from two or more fields. Examples of large-scale interdisciplinary and transdisciplinary team initiatives are the NCI, National Institute of Drug Abuse (NIDA), and National Institute on Alcohol Abuse and Alcoholism (NIAAA) Transdisciplinary Tobacco Use Research Centers (TTURCs)[71]; the NCI Transdisciplinary Research on Energetics and Cancer (TREC) Centers[72]; the Centers for Excellence in Cancer Communications Research (CECCR)[73]; the National Institute of Environmental Health Sciences (NIEHS)[64]; the National Institute on Aging (NIA)[64]; the NIH Office of Behavioral and Social Sciences Research (OBSSR)[64]; the NCI Centers for Population Health and Health Disparities (CPHHD)[64]; and the National Center for Research Resources (NCCR) Clinical and Translational Science Centers (CTSC).[13,74]

The distinctions among unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary forms of scientific collaboration are directly relevant to the development of criteria for gauging the success of team science initiatives. In particular, measures of scientific collaboration and its outcomes should be appropriately matched to the research, training, and translational goals of particular initiatives. A key goal of interdisciplinary and transdisciplinary initiatives, for example, is

[b]As Klein[27] has observed, cross-disciplinary teams, rather than being exclusively multidisciplinary, interdisciplinary, or transdisciplinary in their orientation, often incorporate a mixture of these approaches, each of which may become more or less predominant during different phases of collaboration.

to bridge the perspectives of different fields through the collaborative development of integrative conceptualizations, methodologic approaches, and training strategies. Thus, an important criterion for gauging the success of these initiatives is the extent to which cross-disciplinary integrations are actually achieved by research teams.[27,37,75] These issues are discussed more fully below.

Substantive Concerns and Research Foci Within the Science-of-Team-Science Field

The science-of-team-science field encompasses an amalgam of conceptual frameworks and methodologies that have been used in earlier studies to assess the processes and outcomes of cross-disciplinary research centers and teams. The findings from these studies are part of a rapidly growing database within the science-of-team-science field.[2,3,8,10,31,32,38,74–80] Common themes that offer a basis for integrating prior and future studies of team science initiatives are beginning to emerge, but the field still lacks the conceptual coherence of a more established and widely recognized scientific paradigm.[27,39,66] Greater scientific coherence may be achieved as science-of-team-science scholars reach further agreement about the field's major conceptual, methodologic, and translational concerns. Several substantive concerns and challenges within the science-of-team-science field are outlined below.

Conceptual Concerns

Scholars in the science-of-team-science field have given considerable attention to at least two broad categories of conceptual tasks: (1) defining key terminology and (2) developing theoretical models to account for the circumstances under which team science initiatives are more or less effective.

Defining key terms. It is important to clearly define the major units of analysis and the core subject matter of the science-of-team-science field (e.g., organizational complexity and geographic scope of team science initiatives; different forms of cross-disciplinary research, including multidisciplinary, interdisciplinary, and transdisciplinary collaboration).[8,58] A major challenge is to specify the dimensions of program effectiveness or success as they pertain to team science initiatives. For instance, the quality of scientific work may be defined differently in the context of interdisciplinary and transdisciplinary team initiatives than in unidisciplinary projects. Traditional criteria of scientific quality include conceptual originality; methodologic rigor (e.g., validity and reliability of empirical findings); and the quantity of research outputs produced, such as peer-reviewed publications. In the context of team science initiatives, however, the quality and scope of interdisciplinary and transdisciplinary integration (e.g., the development of integrative conceptualizations and methodologic approaches, the development of training programs bridging two or more fields, the emergence of new hybrid fields of inquiry) are important facets of collaborative scholarship that must be considered in view of their explicit mission to promote scientific integration.[14,27,31,37]

Also, because the scientific, educational, and translational aims of team science initiatives are highly diverse, it is crucial to identify the highest-priority goals and corresponding criteria of success for any given program.[27,36] The overall success of large-scale initiatives (e.g., the NCI TTURC, CECCR, TREC, and CPHHD programs) may be construed differently than the effectiveness of the particular research centers and projects subsumed within them.[9,78] For instance, the cumulative scientific and public health advances associated with large-scale initiatives are qualitatively distinct from the more circumscribed intellectual achievements of a particular research center or team. For both broad-gauged initiatives and their subsidiary projects, key dimensions of program effectiveness (e.g., development of transdisciplinary syntheses, publication of empirical findings, translations of research into clinical practices and policy innovations) are likely to shift as team members progress through the initial, intermediate, and later stages of collaboration.[6,31,36] Collaborative processes and outcomes appear to be stage-dependent, and therefore should be defined differently for near-, mid-, and longer-term phases of team science programs.

Finally, for many team science initiatives, it is important to define not only the distinguishing features of effective scientific collaboration but also the essential facets of successful interdisciplinary and transdisciplinary training (e.g., the career trajectories and intellectual contributions of current and former trainees).[37,62,81–83]

Developing theoretical models and conceptual frameworks. To date, a number of conceptual models have been proposed by science-of-team-science scholars to identify key antecedent conditions, intervening processes, and outcomes associated with team science initiatives and to explain the interrelationships among them (e.g., the presence of institutional supports or constraints at the beginning of an initiative and their impact on subsequent collaborative processes and outcomes).[6,8,55,75,84] For instance, Trochim and colleagues[6] offered an empirically derived logic model (based on the NCI TTURC initiative-wide evaluation study) that accounts for the temporal links observed between the early processes of intellectual collaboration and integration, on the one hand, and subsequent team products—including scholarly publications, transdisciplinary training programs, community health interventions, and public-policy initiatives—on the other; and in this supplement, Holmes et al.[34] and Hall et al.[40] present multistage conceptual frameworks that have guided transdisciplinary research, training, and community intervention efforts within the NCI CPHHD and TREC initiatives, respectively.

Earlier, Stokols and colleagues[31,76] proposed an antecedent–process–outcome model of transdisciplinary science in which several interpersonal, environmental, and organizational antecedents of collaboration are considered, such as the leadership styles of center directors, scientists' commitment to team research, the availability of shared research and meeting space, electronic connectivity among team members, and the extent to which they share a history of working together on prior projects. The intervening processes examined in this model included intellectual, interpersonal, and affective experiences as well as observed or self-reported collaborative behaviors, or both. Examples of these processes are the brainstorming of strategies to create and integrate new ideas, to deal with the cross-disciplinary biases and tensions that often arise in collaborative situations, and to negotiate and resolve conflicts. The antecedent and process variables specified in the model, in turn, influence several near-, mid-, and long-term outcomes of scientific collaboration, including the development of new conceptual frameworks, research publications, training programs, and translational innovations over the course of the initiative. Empirical support for the hypothesized links among antecedent, process, and outcome variables was derived from a longitudinal (5-year) comparative study of the TTURC centers.[31,62,75,77]

Existing models of interdisciplinary and transdisciplinary collaboration raise several questions for future research. For example, certain antecedent conditions present at the outset of a team science project can be conceptualized as collaboration-readiness factors that jointly influence a team's prospects for success over the course of an initiative.[36,40,75] However, the relative contributions of individual collaboration-readiness factors (e.g., the leadership skills of center directors, the availability of shared office and laboratory space, team members' experiences working together on earlier projects) to specific dimensions of collaborative effectiveness (e.g., the quantity of team publications produced as well as their integrative quality and scope, the development of sustainable partnerships with community organizations) are not well-understood and warrant further study.[39]

Also, earlier conceptual models and the field studies on which they are based suggest that the intellectual and scientific outcomes of team science initiatives are strongly influenced by social and interpersonal processes, including team members' collaborative styles and behaviors, interpersonal conflicts, and negotiation strategies.[6,27,75,85] Yet the precise ways in which these social processes influence scientific productivity and transdisciplinary integration are not known. For instance, team members' disagreements about scientific issues may enhance collaborative effectiveness by stimulating new insights and countering tendencies toward "groupthink" among individuals who have worked together for extended periods.[86] On the other hand, long-standing scholarly disagreements that provoke interpersonal conflict can undermine members' trust of each other and their overall performance.[87,88] The empirical relationships between the interpersonal and intellectual dimensions of scientific collaboration remain to be elucidated in future studies.

Methodologic and Measurement Issues

A variety of methods and measures have been used to assess the antecedents, processes, and outcomes of team science initiatives. The most useful or strategic are those that efficiently apply evaluation resources to yield information about the major contributions and limitations of particular programs in a manner that is responsive to the needs of multiple stakeholder groups, including participating scientists and trainees, funding organizations, policymakers, and translational partners in clinical settings and community organizations.[9] Evaluations of team science programs are embedded within overlapping spheres of influence encompassing organizational, institutional, community, regional, national, and global levels, with multiple stakeholders situated at each level.[29,41,42,89] Strategic evaluations incorporate the diverse perspectives of team science interest groups and adopt some or all of the methodologic strategies mentioned below.

Weighted measures of program success. Strategic evaluations begin with a clear vision of what constitutes success within a particular initiative. For example, NCI research and training center initiatives (TTURC, CECCR, CPHHD, TREC) include multiple goals and objectives, ranging from the achievement of: (1) scientific advances in a targeted area of research (e.g., cancer communications or tobacco-use research) resulting from collaborative synergies within and across participating research centers; (2) innovative approaches to and intended outcomes of transdisciplinary research training; (3) translations of scientific research into useful and sustainable clinical practices and community health programs; (4) translations of scientific research into innovative health-policy initiatives; and, ultimately; (5) reductions in health-risk behaviors, health disparities, and the incidence of chronic diseases within a particular population.[9] The relative priorities assigned to these goals may vary from one initiative to another. Thus, evaluations of team science initiatives are most strategic when the criteria for judging program effectiveness are selected and weighted to reflect the highest-priority goals of the particular programs established by funding agencies and other stakeholder groups (e.g., participating scientists, community members, and [in the U.S.] the DHHS and Congressional oversight committees).[29]

Multimethod evaluation. The diversity of goals encompassed by team science initiatives requires the use of multiple quantitative and qualitative methods to measure their intended processes and outcomes as well as to document their unintended ones. The methods used may include surveys and interviews of team members; behavioral observations of centerwide and initiative-wide meetings and collaborative discussions; archival analyses of scientific productivity and impact based on content analyses of written products developed by team members and bibliometric assessments of initiative-based publications; focus-group meetings among scientists, trainees, and staff members participating in an initiative; online diary logs of cross-disciplinary encounters; social-network analyses of collaborative exchanges; and peer reviews by external referees obtained through periodic site visits and independent evaluations of progress reports and collaborative publications. The combined use of survey, interview, observational, and archival measures in evaluations of team science initiatives affords a more complete understanding of collaborative processes and outcomes than can be gained by adopting a narrower methodologic approach.[6,40,83]

Temporal sequencing of evaluative measures. In addition to establishing prioritized criteria for gauging the scientific, training, translational, and public health outcomes of an initiative, attention should be paid to the temporal patterning of evaluation measurements, ranging from assessments of antecedent conditions present at the outset of a collaborative project to early-stage indicators of collaborative synergy and innovation, mid-term markers of scientific and training innovations, and long-term societal (e.g., policy and public health) outcomes.[90] The latter categories of outcomes may be so gradual or temporally lagged that they are not detectable during the period in which an initiative is actively funded.[32] Future studies should be undertaken to assess the postfunding impacts of team science initiatives on science, training, and public health over extended periods (e.g., encompassing one or more decades).[39]

Research design and sampling issues. Team science initiatives pose several challenges related to the sampling of participants and respondents, the establishment of appropriate comparison groups with which to compare initiative-based research centers and teams, and the implementation of field experimental or quasi-experimental research designs. Experimental and quasi-experimental evaluations of team science initiatives are difficult to achieve due to the nonrandom self-selection of scientists into collaborative teams. Appropriate comparison groups may involve teams of scientists working in a particular area of health research (e.g., tobacco science, cancer communications) that applied for a team–center grant and received "nearly fundable" evaluation scores but were not among those applicants funded to establish a transdisciplinary research program. Prospective evaluations of team science initiatives require sufficient numbers of initiative-based research teams and relevant comparison groups, all of which are working in a common research area over the same multiyear period.

To date, the science-of-team-science field has relied almost exclusively on retrospective and prospective case-comparison studies rather than on experimental or quasi-experimental evaluations of research teams, centers, and the multisite initiatives in which they participate. However, longitudinal bibliometric and social-network analyses incorporating multiple comparison groups are currently being implemented at NCI to evaluate the quantitative and qualitative differences in the productivity of health scientists (e.g., tobacco-use researchers) who are working individually on R01 grants, participating in non-initiative–based research centers, or collaborating as members of transdisciplinary team science initiatives. The increasing use of quasi-experimental research designs incorporating multiple comparison groups is an important direction for the science-of-team-science field.[39]

Convergent validation of evaluation data. Regardless of the research designs used to assess program effectiveness, the convergent validation of empirical data is an important benchmark of strategic evaluation. When evaluations of team science initiatives are conducted, the survey and interview assessments of program outcomes offered by participating scientists, trainees, and staff members should be supplemented with peer appraisals provided by external reviewers and consultants. Additional challenges inherent in peer reviews of team science initiatives are discussed by Klein in this supplement[27] and by Laudel.[54]

Translational Strategies

Within the science-of-team-science field, translational strategies can be grouped into two general categories: (1) the use of research findings from team science initiatives as a basis for developing improved clinical practices, disease-prevention strategies, and public health policies; and (2) the use of research findings from the evaluations of team science initiatives as a basis for enhancing the effectiveness of future collaborative research and training programs. Examples of these two kinds of translational research are outlined below.

Translating research findings from team science initiatives into clinical and preventive practices. The NCI SPOREs and the CPHHD initiative emphasize translational research in which scientific findings are used to improve the prevention, detection, diagnosis, treatment—or all of these—of human cancer and to reduce health disparities in medically underserved populations.[34,63,64] Similarly, utilizing research evidence for the improvement of healthcare delivery is a core goal of the NCRR CTSCs.[13] The scientific discovery processes associated with team science initiatives are the initial phase of a transdisciplinary action–research cycle in which team science investigators work closely with community health practitioners and policymakers to translate their findings into improved therapeutic and preventive practices.[55] Community-based coalitions consisting of health scientists and practitioners and intersectoral partnerships between public and private organizations provide the collaborative contexts in which research findings produced by scientific teams are eventually translated into practical applications.[3,43,91] Examples of university–community partnerships that have produced effective and sustainable translations of cancer research findings into community health promotion and disease-prevention strategies are described by Emmons et al.[44]

Translating research findings from team science evaluation studies to enhance future initiatives. This second category of translational research applies the findings from team science evaluation studies to improve the design and effectiveness of ongoing and future collaborative research and training programs. In the case of ongoing initiatives, formative evaluation strategies can be used for continuous quality improvement by providing team science participants with regular (e.g., quarterly, annual) feedback about their collaborative processes and outcomes.[31,92,93] When future team science initiatives are designed, collaboration readiness audits based on the findings from the evaluations of prior team science programs can be administered to assess a team's prospects for collaborative success and to identify opportunities for strengthening institutional and environmental supports for cross-disciplinary research and training.[75] Also, workshops and training modules can be implemented to familiarize researchers and trainees with the challenges inherent in team-based projects and the steps they can take to improve their chances for success. These translational strategies contribute toward building greater capacity for scientific collaboration in team science initiatives.[40]

Earlier research on team performance suggests that the structural complexity of team science initiatives is closely related to the collaborative challenges and coordination constraints encountered by team members.[36] Collaborative research and training programs that span multiple organizations, geographic sites, scientific disciplines, and levels of analysis may require greater institutional and organizational investments in collaboration-readiness resources to ensure programmatic success than those that are less complex.[55] The empirical links among program complexity; collaboration readiness; and cumulative research, training, and translational outcomes of team science initiatives should be examined in future studies.

Goals and Organization of This Supplement on the Science of Team Science

The present supplement is based on the proceedings of the NCI Conference on the Science of Team Science held in Bethesda MD during October 2006, cosponsored by the NCI, the NIH OBSSR, and the American Psychological Association.[33] The purposes of the NCI conference were to address ambiguities and gaps in the science-of-team-science literature, promote greater integration of knowledge in this field, and identify key issues for future investigation. As a prelude to this event, the NCI convened a group of science-of-team-science scholars in October 2005 to assess the state of the knowledge in the field, identify the most pressing questions for future study, and articulate major goals and strategies for the 2006 conference. The intent of the planning meeting was to build on and go beyond the issues addressed in earlier scholarly discussions of the implementation and evaluation of large-scale, cross-disciplinary science and training programs (e.g., National Academy of Sciences [NAS] Convocation on Facilitating Interdisciplinary Research; NAS Conference on Bridging Disciplines in the Brain, Behavioral, and Clinical Sciences; National Research Council Conference on Interdisciplinary Research; NIH Bioengineering Consortium Symposium on Catalyzing Team Science).[5,21,94,95] In particular, participants were asked to identify cutting-edge issues and themes that had received relatively little attention in prior meetings and research and to draft an agenda of high-priority questions for future study.

During the day-long discussions at the 2005 planning meeting, it was decided that the 2006 meeting would incorporate structured panel sessions organized around the conference themes; peer-reviewed poster presentations; opportunities for informal discussion; and a series of commissioned papers to address high-priority research, training, and translational questions for future investigation.[33] The commissioned papers were intended to integrate existing knowledge in the science-of-team-science field and to open new avenues of research on a variety of previously neglected topics. These high-priority topics for future research are addressed in the articles presented in this supplement and are outlined below.

Developing Integrative Conceptualizations of Team Science Processes and Outcomes

Earlier conferences and publications revealed important facets of team-based science and training (e.g., institutional strategies for facilitating cross-disciplinary research, metrics for evaluating collaborative processes and outcomes), but the findings from science-of-team-science studies remain relatively disjointed and lack theoretical grounding and interpretation. Some research reports go relatively unnoticed as chapters in edited volumes published in several different countries or as reports posted on websites that remain unknown to many science-of-team-science scholars. Sorely needed are new conceptualizations of the science-of-team-science field that are informed by an international perspective and by integrative frameworks for organizing and interpreting the findings from prior studies. Klein's article[27] addresses these needs by offering an integrative approach to the evaluation of interdisciplinary and transdisciplinary collaboration—organized around seven core principles or themes—and an integrative assessment of empirical knowledge in this field, viewed from an international perspective. Additionally, the present article and the ones by Kessel and Rosenfield,[38] Croyle,[9] and Syme[35] in this supplement provide overviews of the science-of-team-science field in terms of its major research, training, and translational concerns, and identify for future investigation several topics that have received little attention in prior studies.

Implementing Team Science Initiatives Selectively and Strategically

Earlier studies[10,31,36,55] suggest that cross-disciplinary team research centers and programs are not uniformly successful. In some situations, smaller-scale unidisciplinary projects may be more feasible and likely to succeed than larger, team-based initiatives. Also, certain research questions may be more amenable than others to interdisciplinary and transdisciplinary approaches. Thus, cross-disciplinary collaboration should be viewed as a means for achieving the desired scientific, training, and translational goals rather than as an end in and of itself. That is, investments in team-based initiatives should be reserved for those settings and research topics that are most suited to and would benefit most from collaborative approaches. An important goal for science-of-team-science research is to facilitate "smarter" science, in which particular approaches (e.g., single-investigator versus team-based projects; unidisciplinary versus multidisciplinary, interdisciplinary, or transdisciplinary initiatives) are closely matched to the unique talents and predilections of the participating scientists, the institutional contexts in which they work, and particular research topics and fields (some of which may be more amenable to cross-disciplinary integration than others, as noted by Hays[45]).

Yet conceptual frameworks that enable researchers and their host organizations to forecast when and where team science initiatives will be more or less effective have been lacking. Accordingly, the ecology of team science by Stokols and colleagues[36] in this supplement is intended to provide an integrative typology of contextual factors that have been found to jointly influence collaborative effectiveness across a variety of research and community settings. The typology is based on a review of empirical findings from the fields of social psychology, organizational behavior, information science, community health promotion, and team science evaluation. It offers a conceptual starting point for developing more fine-grained analyses of high-leverage variables (i.e., those that most strongly determine the success of team-based initiatives). Examples of contextual factors that appear to be especially strong determinants of collaborative effectiveness in research settings are discussed below.

The Impact of Interpersonal Processes and Leadership Styles on Scientific Collaboration

Prior evaluations of team science initiatives suggest that the social organization of research teams strongly influences their capacity to achieve scientific or intellectual integration.[6,27,36,75] Several interpersonal processes may directly influence collaborative effectiveness in research settings. To the extent that team members have worked together previously and share a strong commitment to scientific collaboration, they may be better able to coordinate their efforts and accomplish their research, training, and translational goals in subsequent team science projects.[31,40,76] On the other hand, interpersonal conflicts among team members (especially those persisting over long periods) undermine mutual trust and hinder collaborative processes and outcomes.[10,85,88,96] Among the factors that most strongly influence the quality of social interactions in collaborative settings are the abilities and styles of team leaders. Although the links between leadership and collaborative effectiveness have been studied extensively in nonscientific settings,[97–100] they have received relatively little attention in the science-of-team-science field. This gap in science-of-team-science knowledge is directly addressed in the supplement article by Gray,[46] who offers an empirically based conceptualization of three types of leadership tasks that promote transdisciplinary collaboration among leaders of scientific teams. Her analysis of the ways in which leadership styles and abilities influence scientific collaboration provides a conceptual foundation for future research on this topic.

Another important facet of scientific collaboration are the social networks that exist among researchers and the ways in which they influence patterns of communication and cross-disciplinary integration. The article by Provan and colleagues[42] summarizes an empirical study of social networks among scientists working in the field of tobacco harm reduction. Communications among participating tobacco harm–reduction scientists from multiple fields that involve only exchanges of information are considered interdisciplinary, whereas those that lead to the creation of synergistic products (e.g., multi-authored publications) are defined as transdisciplinary. The analyses of network data provided by Provan et al. reveal that homophily, or the tendency to interact with others whose backgrounds are similar to a person's own (evidenced by intradisciplinary network ties), is more prevalent than heterophily (defined as cross-disciplinary communications among network members). Moreover, nonsynergistic interdisciplinary interactions are much more common than transdisciplinary transactions that result in collaborative research outcomes. These data, along with the findings from earlier research, highlight scientists' strong tendencies to affiliate with colleagues whose disciplinary perspectives are similar to their own, and the need to better understand the circumstances under which scientists achieve and sustain cross-disciplinary collaboration and integration.[75,101]

Developing Cyber-Infrastructures to Support Scientific Collaboration

Interpersonal processes (e.g., communication networks, conflict-resolution strategies, leadership styles) are contextual factors that directly influence a team's readiness for collaboration at the outset of a project and their capacity to work together effectively over extended periods. Additional determinants of collaborative capacity and long-term success are the technologic resources (e.g., intranet and Internet connectivity, grid computing infrastructures, data-mining strategies) that enable team members to communicate and integrate diverse sets of data effectively over the course of a team science project.[102] These facets of technologic infrastructure and expertise and their influence on scientific collaboration have received attention in the fields of information science and organizational behavior, but warrant further investigation in the context of team science research and training programs.[36] The ways in which cyber-infrastructures can support successful scientific collaboration spanning multiple disciplines and research sites, and an agenda of related questions for future science-of-team-science studies, are discussed by Hesse in this supplement.[47]

Conceptualizing and Measuring Distinctive Features of Cross-Disciplinary Training

On the one hand, distinctions among multidisciplinary, interdisciplinary, and transdisciplinary forms of cross-disciplinary (versus unidisciplinary) research have received considerable attention among science-of-team-science scholars. On the other hand, these same distinctions, as they relate to strategies of cross-disciplinary training, have been relatively neglected.[62,82,83] Nash's article[37] in this supplement confronts current gaps in the understanding of cross-disciplinary education by offering a broad conceptualization of multidisciplinary, interdisciplinary, and transdisciplinary training and their respective goals. Compared to multidisciplinary and interdisciplinary approaches, transdisciplinary training is uniquely defined by its intention to produce scholars who synthesize theoretical and methodologic perspectives spanning multiple disciplines and analytic levels. Nash distinguishes among different forms of transdisciplinary training, including single-mentor and team-mentoring apprenticeship models, and transdisciplinary training programs that are either broad or narrow in their analytic scope (e.g., in which trainees learn to integrate the perspectives of disciplines sharing the same or widely different levels of analysis). Nash also outlines intrapersonal, interpersonal, and systems-level constraints on—as well as facilitators of—transdisciplinary training processes and outcomes. Finally, his analysis highlights the importance of developing new methods and metrics for evaluating transdisciplinary training, and suggests new directions for research in this area.

Translating Team Science into Effective Clinical, Community Health, and Policy Initiatives

Many large-scale team science initiatives are designed to foster translations of scientific knowledge into improved clinical practices, community health outcomes, and public policies (e.g., statewide taxation of cigarette sales).[13,63,64] However, the processes by which scientific evidence from team science initiatives is incorporated into clinical and community-based programs for health improvement are not well understood.[3] A useful starting point for the development of community-based health initiatives is the transdisciplinary integration of research findings on a particular topic drawn from multiple fields and levels of analysis. For instance, Hiatt and Breen's article[19] in this supplement offers a broad-gauged transdisciplinary synthesis of research evidence documenting the role of social factors in cancer etiology and the ways in which social, behavioral, psychological, and biologic variables as well as the healthcare system jointly influence cancer incidence, survival, and mortality rates. Hiatt and Breen's analysis provides conceptual grounding for developing more comprehensive strategies of cancer prevention and control than have been available in the past.

Emmons and colleagues[44] describe several cases in which the scientific findings obtained through team science initiatives at a university-based cancer center were translated into novel health-communication programs for disease prevention. Examples of these translational initiatives are the Harvard Colorectal Cancer Risk Assessment and Communication Tool for Research and two public Internet sites, Your Cancer Risk and Your Disease Risk.[103] Emmons and colleagues note that the features and functionality of these award-winning websites were influenced by transdisciplinary collaboration among scholars from several different fields. They also describe other translational programs designed collaboratively with non-university partners through community-based participatory research strategies,[104] including the Massachusetts Community Network for Cancer Education, Research, and Training. Taken together, the supplement articles by Hiatt and Breen[19] and Emmons et al.[44] highlight the value of transdisciplinary research findings and conceptual frameworks as a basis for developing novel and sustainable interventions for disease prevention.

Improving the Transfer of Knowledge Across Team Science Initiatives and Evaluation Studies

Another type of translational challenge facing the science-of-team-science field is to improve the transfer of knowledge across multiple initiatives and evaluation studies. Too often, the lessons learned over the course of an initiative are not effectively communicated or transferred to other research organizations and scientists who are contemplating or already engaged in subsequent team science programs.[6,9,75] Investments in team science evaluation studies become more cost effective and strategic to the extent that their conceptual integrations, empirical findings, methodologic tools, and translational innovations are made available to current or prospective members of other initiatives. Hiatt and Breen's analysis[19] of social factors in disease etiology exemplifies a conceptual tool that can be used to guide future research, training, and translation initiatives in the field of cancer control. Similarly, Holmes and colleagues[34] summarize several methodologic lessons learned through their multilevel analyses of health disparities that can be of benefit to participants in future transdisciplinary team science initiatives.

Similarly, new methods and metrics for gauging the effectiveness of a particular team science program can be used later to guide the design and evaluation of other team initiatives once their reliability and validity have been established. The development of new methods for evaluating team science is the focus of two additional articles in this supplement. Hall and colleagues[40] present initial findings from the 2006 NCI TREC Year-One evaluation study in which a new online survey protocol was developed to assess the levels of institutional and interpersonal readiness for transdisciplinary collaboration during the early stages of a 5-year initiative. Empirical links among several dimensions of collaborative readiness, including the availability of shared research facilities; investigators' history of working together on prior projects; and their endorsement of unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary research perspectives, were examined in this study. Also, Mâsse and colleagues[48] summarize new analyses of survey data obtained from tobacco scientists participating in the first 5-year phase of the NCI TTURC initiative. The survey measures and the findings from this study—conducted as part of the NCI evaluation of large initiatives (ELI)[6,31]—exemplify new tools for assessing the impact of interpersonal processes (e.g., collaborative experiences and behaviors) on scientific integration and productivity. These methods and metrics are potentially applicable to the evaluations of other initiatives.

Finally, Kessel and Rosenfield[38] provide a broad review of earlier transdisciplinary research, training, and translational programs as a basis for identifying insights and guidelines that can be used to improve the design and evaluation of future initiatives. Their findings are directly relevant to the goal of enhancing the transfer of knowledge from prior team science initiatives and evaluation studies to subsequent ones.

Understanding the Systemic Contexts of Team Science Initiatives and Their Evaluation

Another relatively neglected topic within the science-of-team-science field is the influence of systemic factors (e.g., institutional supports for interdisciplinary and transdisciplinary collaboration, public and private investments in large-scale research initiatives, societal concerns about the accountability of scientific research) on the design, functioning, and evaluation of team science initiatives.[29,42,89] These issues are addressed in several of the supplement articles. Leischow and colleagues[41] present an overview of systems theory and the ways in which systems thinking can be used to promote public health. A key principle of systems theory is that socio-technical systems (e.g., team science research initiatives) are embedded within broader systemic units (e.g., the Division of Cancer Control and Population Sciences [DCCPS] of NCI) that administer several large initiatives that in turn are nested within larger entities and spheres of influence (e.g., the NIH).[105,106] An advantage of systems thinking is that it reveals the interdependencies among systemic units that operate at these different levels.

For instance, Croyle[9] describes four large-scale transdisciplinary research and training initiatives (TTURC, CECCR, CPHHD, TREC) that are directed by DCCPS within NCI. Because DCCPS serves as the coordinating unit for these programs, lessons learned from the evaluations of the first initiatives to be implemented (TTURC and CECCR) have been incorporated into the design of subsequent programs (CPHHD and TREC).

This transfer of knowledge among several large-scale initiatives has the potential advantage of enhancing the cost effectiveness of DCCPS's and NCI's investments in transdisciplinary science and training programs.

At a broader institutional level, the article by Hays[45] in this supplement (and the papers presented by Farber[107] and Kington[11] at the 2006 NCI conference on the science of team science) describe the NIH Roadmap and OPASI initiatives, both of which are intended to promote greater integration among the disciplines represented within the various institutes that constitute NIH. The design and mission of these initiatives have been informed not only by health research and the assessments of the scientific readiness[45] of particular fields for transdisciplinary integration, but also by societal concerns about public health and the accountability of science to society as a whole.[9,14] Both the Roadmap and OPASI initiatives encompass several other interrelated team science research and training programs, coordinated by multiple institutes at NIH, whose goals are closely aligned with the Roadmap initiative's emphasis on transdisciplinary scientific integration, training, and translation (e.g., the ambitious Clinical Translational Science Awards initiative).[13,29,74] The Roadmap and OPASI initiatives thus provide a strategic framework and mission for organizing several subsidiary team-based programs.

Also within the context of the NIH, Mabry and colleagues[49] describe the strategic mission and cross-disciplinary initiatives supported by OBSSR. Systems principles drawn from the fields of social ecology, populomics, and informatics have been integrated with the biomedical concerns of the Human Genome Project and incorporated into the various programs administered by OBSSR.[16,108–111] The broad biopsychosocial and ecologic vision reflected in OBSSR's strategic plan exemplifies an application of systems thinking to broaden the conceptual scope, the positive health impacts, and the cost effectiveness of large-scale transdisciplinary initiatives.

Federal funding agencies such as the NIH are but one of several potential contributors to the development of transdisciplinary health science and the improvement of public health outcomes. Shen's article[43] in this supplement calls for the establishment of cross-sectoral team science, and underscores the importance of forging new collaborative relationships among private corporations and foundations, public research agencies, and nongovernmental organizations for the purpose of funding and sustaining transdisciplinary health science and improving public health. This is an exciting and potentially fruitful direction for the science-of-team-science field.

The concluding article by Hall and colleagues[39] recaps major themes reflected in the supplement and identifies promising directions for future research organized around key programmatic challenges related to the refinement of science-of-team-science terminology, conceptual frameworks, research methods, transdisciplinary training strategies, cross-sectoral partnerships, and sustainable funding mechanisms. For instance, it will be important in future science-of-team-science research to more clearly conceptualize and measure the construct of readiness for collaboration. This concept has been defined variously in terms of individual and group research orientations,[40,69] organizational and technologic resources that enhance capacity for collaboration,[36,47,57] and the scientific readiness of different fields for collaborative integration.[41,45] Yet, as Hall et al.[39] observe, little is currently known about how these different dimensions of collaborative readiness jointly influence the effectiveness of transdisciplinary initiatives.

Summary

The preceding discussion offers an overview of the science-of-team-science field in terms of its major conceptual, methodologic, and translational concerns. This field encompasses a wide array of research projects and strategies aimed at better understanding, evaluating, and managing circumstances that influence the effectiveness of large-scale team science initiatives. Common themes are beginning to emerge in the literature, but several gaps in the science-of-team-science knowledge base remain to be addressed in future studies. The 2006 NCI conference on the science of team science and the present supplement were organized for the purposes of identifying and analyzing several cutting-edge issues that had received little or no attention in prior science-of-team-science meetings and publications. It is hoped that the articles included in this supplement will help to establish the foundation for achieving greater clarity and integration in science-of-team-science research and for advancing the field's scientific, training, and translational goals.

This article is based on a paper presented at the NCI conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research on October 30–31, 2006, in Bethesda MD. The authors gratefully acknowledge support for this manuscript provided by an IPA contract to Daniel Stokols from the Office of the Director, DCCPS of the NCI; and by Cancer Research Training Award fellowships to Kara L. Hall and Brandie K. Taylor.

No financial disclosures were reported by the authors of this paper.

References

1. Klein JT. Crossing boundaries: knowledge, disciplinarities, and interdisciplinarities. Charlottesville VA: University of Virginia Press, 1996.
2. Laudel G, Origgi G. Introduction to a special issue on the assessment of interdisciplinary research. Research Evaluation 2006;15:2–4.

3. Maton KI, Perkins DD, Altman DG, et al. Community-based interdisciplinary research: introduction to the special issue. Am J Community Psychol 2006;38:1–7.
4. Nass SJ, Stillman B. Large-scale biomedical science: exploring strategies for future research. Washington DC: The National Academies Press, 2003.
5. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005. www.nap.edu/catalog.php?record_id=11153#toc.
6. Trochim WM, Marcus SE, Mâsse LC, Moser RP, Weld PC. The evaluation of large research initiatives: a participatory integrated mixed-methods approach. Am J Eval 2008;29:8–28.
7. Wuchty S, Jones BF, Uzzi B. The increasing dominance of teams in production of knowledge. Science 2007;316:1036–9.
8. Bruun H, Hukkinen J, Huutoniemi K, Klein JT, eds. Promoting interdisciplinary research: the case of the academy of Finland. Helsinki, Finland: The Academy of Finland, 2005.
9. Croyle RT. The National Cancer Institute's transdisciplinary centers initiatives and the need for building a science of team science. Am J Prev Med 2008;35(2S):S90–S93.
10. Kahn RL. An experiment in scientific organization. Chicago IL: The John D. and Catherine T. MacArthur Foundation, Program in Mental Health and Human Development. A MacArthur Foundation Occasional Paper, 1993. http://www.macfound.org/atf/cf/%7BB0386CE3-8B29-4162-8098-E466FB856794%7D/experiment_in_scientific_organization.pdf.
11. Kington R. Goals and directions of the OPASI initiative at NIH. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13474.
12. National Academy of Sciences. The NAS Keck futures initiative. 2003. http://www.keckfutures.org.
13. National Center for Research Resources. Clinical and translational science awards to transform clinical research. 2006. www.ncrr.nih.gov/ncrrprog/roadmap/CTSA_9-2006.asp.
14. NIH. NIH roadmap for medical research: interdisciplinary research. 2003. nihroadmap.nih.gov/interdisciplinary/index.asp.
15. Robert Wood Johnson Foundation. RWJF active living research program. www.rwjf.org/applications/solicited/npo.jsp?FUND_ID=55113.
16. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006;33:515–31.
17. Brainard J. U.S. agencies look to interdisciplinary science. Chron High Educ 2002;48:A20.
18. Esparza J, Yamada T. The discovery value of "Big Science." J Exp Med 2007;204:701–4.
19. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–S150.
20. Kahn RL, Prager DJ. Interdisciplinary collaborations are a scientific and social imperative. The Scientist 1994:12.
21. Pellmar TC, Eisenberg L, eds. Bridging disciplines in the brain, behavioral, and clinical sciences. Washington DC: IOM/The National Academies Press, 2000.
22. Smedley BD, Syme SL, eds. Promoting health: intervention strategies from social and behavioral research. Washington DC: The National Academies Press, 2000.
23. Breckler S. The importance of disciplines. Psychological Science Agenda 2005;19:1–2.
24. Marks AR. Rescuing the NIH before it is too late. J Clin Invest 2006;116:844.
25. Weissmann G. Roadmaps, translational research, and childish curiosity. FASEB J 2005;19:1761–2.
26. Brainard J. New science measures released by OMB. Chron High Educ 2002;48:A25.
27. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
28. Mervis J. Science policy. NSF begins a push to measure societal impacts of research. Science 2006;312:347.
29. Morrison L. The CTSAs, the Congress, and the scientific method. J Investig Med 2008;56:7–10.
30. Smith R. Measuring the social impact of research. BMJ 2001;323:528.
31. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
32. Abrams DB, Leslie FM, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res 2003;5(1S):S5–S10.
33. National Cancer Institute. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13474; videocast.nih.gov/Summary.asp?File=13471.
34. Holmes JH, Lehman A, Hade E, et al. Challenges for multilevel health disparities research in a transdisciplinary environment. Am J Prev Med 2008;35(2S):S182–S192.
35. Syme SL. The science of team science: assessing the value of transdisciplinary research. Am J Prev Med 2008;35(2S):S94–S95.
36. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
37. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.
38. Kessel FS, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. Am J Prev Med 2008;35(2S):S225–S234.
39. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med 2008;35(2S):S243–S249.
40. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
41. Leischow SJ, Best A, Trochim WM, et al. Systems thinking to improve the public's health. Am J Prev Med 2008;35(2S):S196–S203.
42. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
43. Shen B. Toward cross-sectoral team science. Am J Prev Med 2008;35(2S):S240–S242.
44. Emmons KM, Viswanath K, Colditz GA. The role of transdisciplinary collaboration in translating and disseminating health research: lessons learned and exemplars of success. Am J Prev Med 2008;35(2S):S204–S210.
45. Hays TC. The science of team science: commentary on measurements of scientific readiness. Am J Prev Med 2008;35(2S):S193–S195.
46. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
47. Hesse BW. Of mice and mentors: developing cyber-infrastructure to support transdisciplinary scientific collaboration. Am J Prev Med 2008;35(2S):S235–S239.
48. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008;35(2S):S151–S160.
49. Mabry PL, Olster DH, Morgan GD, Abrams D. Interdisciplinary and systems science to improve population health: a view from the NIH Office of Behavioral and Social Sciences Research. Am J Prev Med 2008;35(2S):S211–S224.
50. Dunbar K. How scientists really reason: scientific reasoning in real-world laboratories. In: Sternberg RJ, Davidson J, eds. Mechanisms of insight. Cambridge MA: MIT Press, 1995.
51. Hess DJ. Science studies: an advanced introduction. New York: New York University Press, 1997.
52. Klahr D, Simon HA. Studies of scientific discovery: complementary approaches and convergent findings. Psychol Bull 1999;125:524–43.
53. Latour B, Woolgar S. Laboratory life: the construction of scientific facts. Princeton NJ: Princeton University Press, 1986.
54. Laudel G. Conclave in the Tower of Babel: how peers review interdisciplinary research proposals. Res Eval 2006;15:57–68.
55. Stokols D. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
56. Ramadier T. Transdisciplinarity and its challenges: the case of urban studies. Futures 2004;36:423–39.
57. Olson GM, Olson JS. Distance matters. Human-Computer Interaction 2000;15(2/3):139–78.
58. Klein JT. A conceptual vocabulary of interdisciplinary science. In: Weingert P, Stehr N, eds. Practising interdisciplinarity. Toronto: University of Toronto Press, 2000.
59. Lawrence RJ, Despres C. Futures of transdisciplinarity. Futures 2004;36:397–405.
60. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
61. NIH. Types of grant programs. 2008. grants.nih.gov/grants/funding/funding_program.htm.

62. Nash JM, Collins BN, Loughlin SE, et al. Training the transdisciplinary scientist: a general framework applied to tobacco use behavior. Nicotine Tob Res 2003;5(1S):S41–S53.
63. National Cancer Institute. Guidelines: specialized programs of research excellence (SPOREs). 2001. spores.nci.nih.gov/.
64. National Cancer Institute. Centers for population health and health disparities. 2006. cancercontrol.cancer.gov/populationhealthcenters/.
65. Turner S. What are disciplines? And how is interdisciplinarity different? In: Weingart P, Stehr N, eds. Practising interdisciplinarity. Toronto: University of Toronto Press, 2000.
66. Kuhn T. The structure of scientific revolutions. Chicago: University of Chicago Press, 1970.
67. Klein JT. Interdisciplinarity: history, theory and practice. Detroit MI: Wayne State University Press, 1990.
68. Hirsch Hadorn G, Hoffmann-Riem H, Biber-Klemm S, et al., eds. Handbook of transdisciplinary research. New York: Springer, 2008.
69. Kessel FS, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
70. td-net. Network for transdisciplinarity in sciences and humanities. 2005. www.transdisciplinarity.ch.
71. National Cancer Institute. Transdisciplinary tobacco use research centers. 2006. dccps.nci.nih.gov/tcrb/tturc/.
72. National Cancer Institute. Transdisciplinary research on energetics and cancer. 2006. https://www.compass.fhcrc.org/trec/.
73. National Cancer Institute. Health communication and informatics research: NCI centers of excellence in cancer communications research. 2006. cancercontrol.cancer.gov/hcirb/ceccr/.
74. Zerhouni EA. Translational and clinical science—time for a new vision. N Engl J Med 2005;353:1621–3.
75. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
76. Fuqua J. Transdisciplinary scientific collaboration: an exploration of the research process [dissertation]. Irvine (CA): School of Social Ecology, University of California, 2002.
77. Fuqua J, Stokols D, Gress J, Phillips K, Harvey R. Transdisciplinary collaboration as a basis for enhancing the science and prevention of substance use and "abuse." Subst Use Misuse 2004;39:1457–514.
78. Morgan G, Kobus K, Gerlach KK, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003;5(1S):S11–S19.
79. Rhoten D. Final report: a multi-method analysis of the social and technical conditions for interdisciplinary collaboration. 2003. www.hybridvigor.net/publications.pl?s=interdis.
80. Younglove-Webb J, Gray B, Abdalla CW, Purvis Thurow A. The dynamics of multidisciplinary research teams in academia. The Review of Higher Education 1999;22:425–40.
81. Lattuca LR. Creating interdisciplinarity. Nashville TN: Vanderbilt University Press, 2001.
82. Mitrany M, Stokols D. Gauging the transdisciplinary qualities and outcomes of doctoral training programs. J Planning Educ Res 2005;24:437–49.
83. Rhoten D, Parker A. Education: risks and rewards of an interdisciplinary research path. Science 2004;306:2046.
84. Weingart P, Stehr N, eds. Practising interdisciplinarity. Toronto: University of Toronto Press, 2000.
85. Sonnenwald DH. Scientific collaboration: a synthesis of challenges and strategies. In: Cronin B, ed. Annual Review of Information Science and Technology, vol. 41. Medford NJ: Information Today, Inc., 2007.
86. Janis I. Groupthink: psychological studies of policy decisions and fiascoes. 2nd ed. Boston MA: Houghton Mifflin, 1982.
87. Tuckman BW. Developmental sequence in small groups. Psychol Bull 1965;63:384–99.
88. Sonnenwald DH. Managing cognitive and affective trust in the conceptual R&D organization. In: Houtari M, Iivonen M, eds. Trust in knowledge management and systems in organizations. Hershey PA: Idea Publishing, 2003.
89. Best A, Tenkasi R, Trochim W, et al. Systemic transformational change in tobacco control: an overview of the Initiative for the Study and Implementation of Systems (ISIS). In: Casebeer AL, Harrison A, Mark AL, eds. Innovations in health care: a reality check. London: Palgrave MacMillan, 2006.
90. Walter AI, Helgenberger S, Wiek A, Scholz RW. Measuring societal effects of transdisciplinary research projects: design and application of an evaluation method. Eval Program Plann 2007;30:325–38.
91. Syme SL. Community participation, empowerment, and health: development of a wellness guide for California. In: Schneider Jamner M, Stokols D, eds. Promoting human wellness: New frontiers for research, practice, and policy. Berkeley CA: University of California Press, 2000:78–98.
92. Rossi PH, Freeman HE. Evaluation: a systematic approach. Newbury Park CA: Sage Publications, 1993.
93. Scriven MS. The science of valuing. In: Shadish WR, Jr., Cook TD, Leviton LC, eds. Foundations of program evaluation: theories of practice. Newbury Park CA: Sage Publications, 1991.
94. NIH. BECON 2003 symposium on catalyzing team science (Day 1). 2003 June 23–24; Bethesda MD. videocast.nih.gov/launch.asp?9924.
95. National Research Council. Interdisciplinary research: promoting collaboration between the life sciences and medicine and the physical sciences and engineering. Washington DC: IOM/The National Academies Press, 1990.
96. Maglaughlin KL, Sonnenwald DH. Factors that impact interdisciplinary natural science research collaboration in academia. In: Ingwersen P, Larsen B, eds. Proceedings of the ISSI. 2005 Jul 24–25; Stockholm, Sweden: Karolinska University Press, 2005.
97. Collins J. Level 5 leadership: the triumph of humility and fierce resolve. Harv Bus Rev 2001;79:66–76.
98. Jacobs D, Singell L. Leadership and organizational performance: isolating links between managers and collective success. Soc Sci Res 1993;22:165–89.
99. Kumpfer KL, Turner C, Hopkins R, Librett J. Leadership and team effectiveness in community coalitions for the prevention of alcohol and other drug abuse. Health Educ Res 1993;8:359–74.
100. Hackman JR. Leading teams: setting the stage for great performances. Boston MA: Harvard Business School Press, 2002.
101. Festinger L. A theory of social comparison processes. Human Relat 1954;7:117–40.
102. Olson GM, Olson JS, Zimmerman A, eds. Science on the Internet. Cambridge MA: MIT Press, 2008.
103. Harvard Center for Cancer Prevention. Your disease risk. 2005. www.yourdiseaserisk.harvard.edu/.
104. Minkler M, Wallerstein N, eds. Community-based participatory research for health. San Francisco: Jossey-Bass, 2003.
105. Emery FE, ed. Systems thinking. London: Penguin Books, 1969.
106. Emery FE, Trist EL. Socio-technical systems. In: Churchman CW, Verhulst M, eds. Management science: models and techniques. Oxford, England: Pergamon, 1969.
107. Farber G. An overview of the NIH Roadmap initiative. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13474.
108. Abrams DB. Transdisciplinary paradigms for tobacco prevention research. Nicotine Tob Res 1999;(1S):S15–S23.
109. Gibbons MC. A historical overview of health disparities and the potential of eHealth solutions. J Med Internet Res 2005;7:e50.
110. Stokols D. Translating social ecological theory into guidelines for community health promotion. Am J Health Promot 1996;10:282–98.
111. Tyers M, Mann M. From genomics to proteomics. Nature 2003;422:193–7.

The National Cancer Institute's Transdisciplinary Centers Initiatives and the Need for Building a Science of Team Science

Robert T. Croyle, PhD

Introduction

When the National Cancer Institute (NCI) was reorganized by former Director Richard Klausner, a new Division of Cancer Control and Population Sciences (DCCPS) was established in the Fall of 1997. Under the leadership of Drs. Barbara Rimer and Robert Hiatt, the division rapidly set out to reinvigorate the science of cancer control through the development of new initiatives in surveillance, epidemiology, health services, behavioral, and cancer survivorship research. One important assumption underlying these efforts was that the speed of scientific progress and its effective application to public health problems would depend on the integration of discipline-specific efforts and increased support for collaboration, evidence synthesis, and the science of dissemination.[1] A key strategy for achieving those goals was the development of new transdisciplinary team science research centers, focused on four problem domains that were seen as critical barriers against effective cancer prevention and control: tobacco use, health disparities, obesity, and poor communication. Although these four initiatives were housed within the new Behavioral Research Program within DCCPS, it was clear from the outset that to effectively accomplish the program objectives, both the centers projects and investigators would need to span a wide range of disciplines, from molecular biology to policy studies.

Soon after I moved to NCI in July of 1998 as the first Associate Director for Behavioral Research in DCCPS, I had the privilege of developing the Request for Applications (RFA) for the first of the series of transdisciplinary science initiatives. The Transdisciplinary Tobacco Use Research Centers (TTURCs) were developed and funded in collaboration with the National Institute on Drug Abuse (with the support of Jay Turkkan and Alan Leshner) and the Robert Wood Johnson Foundation (with the support of Nancy Kaufman and Tracy Orleans).[2,3] It is important to remember that in the late 1990s, when this effort was launched, *transdisciplinary* was an unfamiliar term in biomedical and behavioral research. The NIH Roadmap had yet to be conceived. In fact, some members of NCI's Board of Scientific Advisors disputed whether *transdisciplinary* was a word at all!

A lot has changed in the past decade. One scholar, noting the recent popularity of all things *interdisciplinary* or associated with *interdisciplinarity* in academia, complained that "so powerful are the I-words that it is difficult to oppose anything (including top-down allocation of resources) done in their names—and cynical speculations abound that a person or committee's proclaimed commitment to them is strategic, not heartfelt."[4] But despite the skepticism, both universities and research funders have continued to invest in new programs to grow interdisciplinary research. NCI launched the Integrative Cancer Biology Program, Stanford University initiated the Bio-X Program, and several centers, training programs, and research projects were funded through the Interdisciplinary Research component of the NIH Roadmap initiative. One of the most distinctive efforts supports not only a newly constructed physical infrastructure, but also the scientific projects conducted there. The new Janelia Farm facility in Virginia, funded by the Howard Hughes Medical Institute, houses an interdisciplinary neurobiology center for high-risk, collaborative research.[5] Janelia Farms is a grand experiment in a new way of doing science, and many observers will be watching closely to see the outcome.

Two critical concerns emerged from these efforts: (1) the relative merits of these investments versus traditional discipline-specific activities, and (2) how best to ensure their success. Funders and investigators alike are asking: *How do we evaluate interdisciplinary and transdisciplinary team science?*

Once the TTURCs were launched, it immediately became clear that the NIH, including NCI, had no clear metrics for evaluating problem-focused centers initiatives like the TTURCs. In addition, the specific goals of the TTURCs, which included the development of novel transdisciplinary team science and training, were based on assumptions about how best to facilitate scientific progress that had yet to be tested empirically. Therefore, it was clear that the TTURCs presented both a

From the Division of Cancer Control and Population Sciences, National Cancer Institute, Bethesda, Maryland

Address correspondence and reprint requests to: Robert T. Croyle, PhD, Director, National Cancer Institute, Division of Cancer Control and Population Sciences, 6130 Executive Boulevard, Room 6138, Bethesda MD 20892-7338. E-mail: croyler@mail.nih.gov.

Published by Elsevier Inc.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.012

challenge to the science of evaluation and an opportunity to develop new evaluation methods by studying the process and outcomes of transdisciplinary science itself.

The logical next step was to initiate an evaluation methods development effort focused on the assessment of constructs, such as collaboration and transdisciplinarity, that were deemed essential to the process of planning and conducting transdisciplinary science. The ELI (Evalution of Large Initiatives) Project, as we called it, was initially designed as an effort to specify, measure, and understand the transdisciplinary science goals and processes within the TTURCs. However, at the very outset, we also conceived it as a pilot project for a longer-term effort to develop an evaluation toolkit for a variety of large science initiatives. We asked Bill Trochim of Cornell University to lead this initial effort, which is described in a recent publication[6] and in the Masse et al.[7] article in this supplement.

From these early experiences, as well as the challenge of evaluating subsequent centers' initiatives (e.g., Centers for Population Health and Health Disparities, Centers of Excellence in Cancer Communication Research, Transdisciplinary Research in Energetics and Cancer centers), it became clear that an expanded effort focusing on the "science of team science" was merited. We asked Dan Stokols to lead this second phase of the ELI project, which included the evaluation of the Transdisciplinary Research in Energetics and Cancer (TREC) centers, described by Hall et al.[8] in this issue, and the planning of the Science of Team Science conference that formed the basis of this supplement to the *American Journal of Preventive Medicine*.[7–21]

Building a Case for the Science of Team Science

Understandably, the consideration of new methods for evaluating scientific initiatives to complement the traditional peer review, expert opinion model raises concern among investigators. Although improvements can always be made, NIH's peer review system has served as a model both within and outside of the U.S. But it is important to recognize that funders have fiduciary, strategic, and societal responsibilities that go well beyond those that are shared by the individual investigator or scientific discipline. Federal agencies have to be accountable to a broader and more diverse set of constituencies for the productivity and impact of sponsored research. At the same time, the credibility of the peer review process for biomedical and behavioral research may be diminished if scientists strenuously advocate for the application of a scientific epistemology to their subjects but resist its application to themselves. To put it more bluntly, if we don't develop methods to evaluate our science, someone else will. Basic science is especially vulnerable, given the time lag until impact. As Gallagher[22] has argued, "Blind implementation of half-baked outcomes assessment by apparatchiks is the nightmare scenario. It could be the death of curiosity-driven research and must be actively guarded against by scientists." Our strategy for navigating these conflicting priorities has been to focus our evaluation development efforts not on the evaluation of individual studies or grants (appropriately, the domain of traditional peer review) but on evaluation at a higher level, the level of large initiatives that support a multidisciplinary group of grants or research networks.

In addition to avoiding ill-informed evaluations by nonscientists, there are at least four compelling reasons for accelerating our efforts to develop a science of team science now. First, team science is here, and the trend is not limited to biomedical research. A massive study by Wuchty et al.[23] of 19.9 million research articles and 2.1 million patent records associated with a wide range of disciplines showed steady growth in both the proportion of publications and patents by teams and the size of those teams. Second, concerns continue to be raised within the scientific community itself about the productivity of science and the appropriate balance between large-scale team science and traditional, individual-investigator-initiated studies. The National Science Foundation, for example, found that despite increases in funding, the overall number of publications by U.S. scientists remained flat.[24] This may not be a bad thing, if, as the Wuchty et al. analysis indicated, investigators who coalesce in teams are producing articles with greater impact.

Third, there are well-established bodies of research, including methods and theories, which have yet to be utilized in most studies of scientific initiatives. One reason is the existence of disciplinary silos, the very silos that transdisciplinary team science seeks to penetrate. Much of this work comes from disciplines within the social and behavioral sciences (e.g., work on teams[25] and leadership[26]), but, as the articles in this issue demonstrate, the humanities have much to contribute as well. A science of team science can build an empirical foundation to allow the experiences from one initiative to inform another[27] and produce conceptual frameworks for the integration of science across multiple levels.[28] In addition, it can lend objectivity to the evaluation of processes such as collaboration through the development of quantitative indices, such as bibliometric measures of collaboration.[29]

A fourth argument in favor of building a science of team science is the fundamental importance of training. Education can and should be a science-based activity, but to inform modern team science, we need a better understanding of how and when to initiate interdisciplinary and transdisciplinary experiences. This complex and multifaceted issue can be studied systematically at multiple levels. Sadler and Tai[30] provided one creative example of how debates concerning the sequencing of science courses and their cross-disciplinary benefits (e.g., does a physics course help performance in a later biology course) can be informed by careful educational research. They examined the relationship between high school math and science preparation and performance in college science courses. They found no evidence to support cross-disciplinary benefits of high school science courses (e.g., taking high school physics did not improve performance in college chemistry), but found strong evidence to support cross-disciplinary benefits of high school calculus. In this issue, Nash[13] explores transdisciplinary training at the graduate and postdoctoral levels, suggesting strategies for overcoming the many barriers against success in this domain.

Bridging Team Science with Public Policy

What's in store for transdisciplinary team science in the coming decade? As we continue to advance our ability to rigorously evaluate team science efforts, we also need to gradually but steadily expand the interface between large-scale problem-solving in science and the development of public policy. Traditionally, the National Academies have played an important role in this interface, but only a small minority of the many reports issued by the Academy and Washington DC–area think tanks attracts serious attention from policymakers. Congress is considering whether to revive its Office of Technology Assessment, created in 1972 but defunded in 1995, to facilitate the utilization of science in legislation. Innovations and processes that increase the utilization of scientific evidence in policymaking are sorely needed, but it remains to be seen whether scientists will step up to the plate in sufficient numbers. Too few scientists see it as their responsibility to contribute to the science policy interface. Clearly, funders can play a key role in enabling the participation of scientists in policy research, development and decision making. The Robert Wood Johnson Foundation and the American Cancer Society, for example, have supported projects with this focus, but professional scientific associations and federal agencies could do more to facilitate this interface.

Some governments are experimenting with ambitious new strategies to enable the application of new interdisciplinary knowledge from science and industry to complex societal problems. In the United Kingdom, for example, the Technology Foresight Program[31] has taken on issues such as obesity, addiction, and crime prevention, merging evidence synthesis with policy and budget development, followed by project impact assessments led by cabinet ministers. In the U.S., special commissions, working groups, and tasks forces have been created on a range of topics, but these are rarely accompanied by a sustainable implementation process that outlives changes in political leadership. The opportunities and challenges in integrating transdisciplinary team science leaders and their discoveries with non-academic sectors were well-articulated by Neal Lane, a former Director of the National Science Foundation. His call to action substantiates our reason for supporting this special issue, the need to understand the processes by which large team science efforts can be successful not only in generating new knowledge, but also in changing our strategies for disease prevention and control:

> The successful application of new knowledge and breakthrough technologies, which are likely to occur with ever-increasing frequency, will require an entirely new interdisciplinary approach to policymaking: one that operates in an agile problem-solving environment and works effectively at the interface where science and technology meet business and public policy. It must be rooted in vastly improved understanding of people, organizations, cultures, and nations and be implemented by innovative strategies and new methods of communication. All of this can occur only by engaging the nation's top social scientists, including policy experts, to work in collaboration with scientists and engineers from many fields and diverse institutions on multidisciplinary research efforts that address large but well-defined national and global problems.[32]

No financial disclosures were reported by the author of this paper.

References

1. Hiatt RA, Rimer BK. A new strategy for cancer control research. Cancer Epidemiol Biomarkers Prev 1999;8:955–6.
2. Turkkan JS, Kaufman NJ, Rimer BK. Transdisciplinary tobacco use research centers: a model collaboration between public and private sectors. Nicotine Tob Res 2000;2:9–13.
3. Morgan GD, Kobus K, Gerlach KK, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003:5 Suppl 1:S11–9.
4. Wasserstrom JN. Expanding the I-Word. Chronicle of Higher Education. Jan. 20, 2006:B5.
5. Bhattacharjee Y. Neurobiology on the farm. Science 2006;314:1530–2.
6. Trochim WM, Marcus SE, Masse LC, Moser RP, Weld PC. The evaluation of large research initiatives: a participatory integrative mixed-methods approach. American Journal of Evaluation 2008;29:8–28.
7. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008;35(2S):S151–S160.
8. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
9. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
10. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
11. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
12. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
13. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.

14. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–S150.
15. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
16. Holmes JH, Lehman A, Hade E, et al. Challenges for multilevel health disparities research in a transdisciplinary environment. Am J Prev Med 2008;35(2S):S182–S192.
17. Leischow SJ, Best A, Trochim WM, et al. Systems thinking to improve the public's health. Am J Prev Med 2008;35(2S):S196–S203.
18. Emmons KM, Viswanath K, Colditz GA. The role of transdisciplinary collaboration in translating and disseminating health research: lessons learned and exemplars of success. Am J Prev Med 2008;35(2S):S204–S210.
19. Mabry PL, Olster DH, Morgan GD, Abrams D. Interdisciplinary and systems science to improve population health: a view from the NIH Office of Behavioral and Social Science Research. Am J Prev Med 2008;35(2S):S211–S224.
20. Kessel FS, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. Am J Prev Med 2008;35(2S):S225–S234.
21. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med 2008;35(2S):S243–S249.
22. Gallagher R. Basic research: it's worth it. The Scientist 2005;19:6.
23. Wuchty S, Jones BF, Uzzi B. The increasing dominance of teams in production of knowledge. Science 2007;316:1036–8.
24. Mervis J. U.S. output flattens, and NSF wonders why. Science 2007;317:582.
25. Kozlowski SWJ, Ilgen DR. Enhancing the effectiveness of work groups and teams. Psychological Science 2006;7:77–124.
26. Sternberg RJ. A systems model of leadership: WICS. American Psychologist 2007;62:34–42.
27. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: Lessons learned and implications for active living research. Am J Prev Med 2005;28(2 Suppl 2):202–13.
28. Pescosolido BA. Of pride and prejudice: the role of sociology and social networks in integrating the health sciences. J Health Soc Behav 2006;47:189–208.
29. Diener E. Professional issues in psychological science and a discussion of collaboration indicators. Perspectives on Psychological Science 2006;1:312–5.
30. Sadler PM, Tai RH. The two high-school pillars supporting college science. Science 2007;317:457–8.
31. King DA, Thomas SM. Taking science out of the box—foresight recast. Science 2007;316:1701–2.
32. Lane N. Alarm bells should help us refocus. Science 2006;312:184.

The Science of Team Science

Assessing the Value of Transdisciplinary Research

S. Leonard Syme, PhD

Several years ago, I chaired a committee organized by the IOM to consider the success of our public health efforts to prevent disease. The resulting 493-page report concluded that we were not doing a very good job.[1] The committee offered 18 recommendations intended to improve this situation. The first recommendation was that we needed to develop a better balance between clinical approaches to disease prevention (presently the dominant public health model for most risk factors) and work that recognizes the importance of generic social and behavioral determinants of disease, injury, and disability. The second recommendation was that we needed to develop interventions that took account of a wide range of health determinants that operated at the individual, interpersonal, institutional, community, and policy levels. The main message was that we needed somehow to transcend our disciplinary silos and consider a much broader set of determinants in a far more complex way than we have so far been able to do. Easier said than done. The papers in this supplement to the *American Journal of Preventive Medicine*[2–16] therefore are a timely, important, and badly needed contribution to our work in preventing disease and promoting health.

We all know the problem. Within the next 15 years, the number of people aged >65 in the U.S. will have doubled. Medical care resources in this country are already severely challenged. When the number of older people dramatically increases, the burden on medical care will be beyond anything we can now imagine. The importance of disease prevention in helping to deal with this crisis is obvious. To develop appropriate and effective prevention programs is going to require a new paradigm.

At present, our prevention efforts depend on research to identify disease risk factors so that we can share our acquired wisdom with people at risk. The idea is that these people will then rush home and change behavior to lower their risk. There are three problems with this approach. First, it has proven extraordinarily difficult to identify those risk factors. For the leading cause of death, coronary heart disease, the major identified risk factors (serum cholesterol, high blood pressure, smoking, physical inactivity, obesity) account for less than one half of the coronary heart disease that occurs. Our success in identifying risk factors for other diseases is even less impressive. Second, even when risk factors are identified, it has proven very difficult for people to change their behavior to lower their risk. And third, even when people do successfully reduce their risk, new people continually enter the at-risk population because we rarely identify those forces in the society that cause the problem in the first place.[17] Our silo-based work has not served us well.

The challenge of overcoming this silo approach is overwhelming. Those of us in different silos have been trained quite differently, we have read different kinds of books, we use different languages, we evaluate the quality of research data and evidence quite differently, and we have very different assessments of what it takes to do good research. Oftentimes, we don't even respect one another. Can you imagine these types of problems in an environment where a specific problem needs to be solved? Imagine a company that makes airplanes. In such a company, there must be people representing hundreds of discipline specialties. It is inconceivable that these people would argue about the supremacy of their discipline compared to the others. They have an airplane to build! The challenge of solving the design and construction of the airplane problem clearly would take precedence over turf battles.

It is within the context of this charged and sensitive environment that we welcome this supplement to AJPM[2–16]: There is a paper in this volume that explicitly examines the collaborative process and the way it affects the trust and respect of participants. There is a paper that suggests ways to assess the collaborative process. There is a paper that presents examples of other areas in which transdisciplinary research has in fact worked well. There is a paper that examines the role of leadership in facilitating the transdisciplinary process. There are papers that demonstrate the ways in which transdisciplinary research has been useful in shedding light on the etiology of diseases, on risk factors, and on the translation of findings for more effective intervention programs. And there is a paper discussing the way in which interdisciplinary thinking has become an important dimension of thinking at the NIH.

From the Departments of Epidemiology and Community Health, University of California Berkeley, Berkeley, California

Address correspondence and reprint requests to: S. Leonard Syme, PhD, 577 University Hall, Berkeley CA 94720. E-mail: slsyme@berkeley.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.017

This latter contribution regarding funding raises a pivotal challenge for the future of transdisciplinary work. The NIH is the most important source in the country for funding both research and training in the health field. Overwhelmingly, however, successful research and training grants are awarded for programs (1) that target a specific disease (coronary heart disease, cancer) or a disease-specific risk factor (smoking, obesity); and/or (2) that focus on work at the laboratory, clinical, or population level. Transdisciplinary proposals that seek to look at health more generally or that attempt to integrate work at several levels often have a difficult time in the traditional study section setting that dominates the review process at the NIH; that this landscape is now being reconsidered is refreshing and of critical significance for the future of transdisciplinary work.

Several years ago, the Canadian government decided to develop a National Institutes of Health for Canada. Many of us warned them that if they patterned their NIH along the same lines as our NIH, it would set back for many decades the cause of preventive work. They did subsequently establish the Canadian Institute for Health Research with the usual institutes devoted to cancer, circulatory diseases, arthritis, and diabetes but they also established institutes on population health, aboriginal peoples, health services and policy research, and gender. I served for 5 years on the Advisory Board for the Institute of Population and Public Health, and I can testify to the dramatically different type of considerations that take place when one is free to transcend a narrow focus on specific diseases and disease-specific risk factors. Similarly, the Robert Wood Johnson Foundation has recently developed a post-doctoral training program called Health and Society that specifically emphasizes a transdisciplinary approach to health. The work being done by many of these scholars is truly amazing. So it can be done.

Thomas Kuhn wrote is his classic book, *The Structure of Scientific Revolutions*,[18] that paradigm shifts occur in science when the old ways of making sense of the world are no longer useful or appropriate. The need for a transdisciplinary approach to the study of health and disease is critically needed because the traditional silo approach to these issues clearly is not adequate to the challenges we face. As has been noted, we are not able to identify many disease risk factors; even when we do successfully identify risk factors, it is difficult for people to change their behavior to change their risk profile; and even if people do change their behavior, new people continually take their place because we have failed to identify many of the fundamental societal forces that cause the problem in first place. A new paradigm is needed. The papers in this issue bring together a series of refreshing, imaginative, and urgently needed new perspectives on this problem. This supplement to AJPM is a major contribution to our thinking.

No financial disclosures were reported by the author of this paper.

References

1. Smedley BD, Syme SL, eds. Promoting health: intervention strategies from social and behavioral research. Washington DC: National Academy Press, 2000.
2. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
3. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
4. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
5. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
6. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.
7. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–150.
8. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008;35(2S): S151–S160.
9. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008; 35(2S):S161–S172.
10. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
11. Holmes JH, Lehman A, Hade E, et al. Challenges for multilevel health disparities research in a transdisciplinary environment. Am J Prev Med 2008;35(2S):S182–S192.
12. Leischow SJ, Best A, Trochim WM, et al. Systems thinking to improve the public's health. Am J Prev Med 2008;35(2S):S196–S203.
13. Emmons KM, Viswanath K, Colditz GA. The role of transdisciplinary collaboration in translating and disseminating health research: lessons learned and exemplars of success. Am J Prev Med 2008;35(2S):S204–S210.
14. Mabry PL, Olster DH, Morgan GD, Abrams D. Interdisciplinary and systems science to improve population health: a view from the NIH Office of Behavioral and Social Science Research. Am J Prev Med 2008;35(2S):S211–S224.
15. Kessel FS, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. Am J Prev Med 2008;35(2S):S225–S234.
16. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med 2008; 35(2S):S243–S249.
17. Syme SL. Social determinants of health: the community as an empowered partner. Preventing Chronic Disease 2004;1:1–5.
18. Kuhn TS. The structure of scientific revolutions. Chicago: University of Chicago Press, 1996.

The Ecology of Team Science

Understanding Contextual Influences on Transdisciplinary Collaboration

Daniel Stokols, PhD, Shalini Misra, MS, Richard P. Moser, PhD, Kara L. Hall, PhD, Brandie K. Taylor, MA

Abstract: Increased public and private investments in large-scale team science initiatives over the past two decades have underscored the need to better understand how contextual factors influence the effectiveness of transdisciplinary scientific collaboration. Toward that goal, the findings from four distinct areas of research on team performance and collaboration are reviewed: (1) social psychological and management research on the effectiveness of teams in organizational and institutional settings; (2) studies of cyber-infrastructures (i.e., computer-based infrastructures) designed to support transdisciplinary collaboration across remote research sites; (3) investigations of community-based coalitions for health promotion; and (4) studies focusing directly on the antecedents, processes, and outcomes of scientific collaboration within transdisciplinary research centers and training programs. The empirical literature within these four domains reveals several contextual circumstances that either facilitate or hinder team performance and collaboration. A typology of contextual influences on transdisciplinary collaboration is proposed as a basis for deriving practical guidelines for designing, managing, and evaluating successful team science initiatives.

(Am J Prev Med 2008;35(2S):S96–S115) © 2008 American Journal of Preventive Medicine

Introduction

The growing interest and investment in transdisciplinary team science over the past 2 decades are reflected in the establishment of several large-scale research and training initiatives by both public agencies and private foundations.[1–7] This increasing commitment to transdisciplinary collaboration in science and training stems from the inherent complexity of contemporary public health, environmental, political, and policy challenges (e.g., cancer, heart disease, diabetes, AIDS, global warming, inter-group conflict, terrorism), and the realization that an integration of multiple disciplinary perspectives is required to better understand and ameliorate these problems.[8–12]

The expanded investment in team science and training has prompted greater demands for evidence that they be cost effective and justifiable in terms of their scientific, training, clinical, policy, and health outcomes, especially relative to smaller-scale, discipline-based research projects.[13–16] Team science initiatives typically entail substantial multiyear commitments of monetary, human, and material resources.[17] Critics of team science contend that its value-added contributions to scholarship, training, and public health may not be evident for several decades and are exceedingly difficult to calibrate in rigorous experimental fashion relative to those yielded by smaller-scale, unidisciplinary projects (e.g., single-investigator NIH R01 grants).[18,19]

Even proponents of team science initiatives note that they are highly labor intensive; often conflict-prone; and require substantial preparation, practice, and trust among team members to ensure a modicum of success.[20–22] The labor-intensity of collaborative research programs may pose unique risks to young scholars who are particularly concerned about establishing strong scientific identities within their chosen fields.[23] Consistent with these concerns, a growing number of studies focusing on the processes and outcomes of transdisciplinary scientific collaboration suggest that the effectiveness of team initiatives is highly variable and depends greatly on certain contextual circumstances and collaborative readiness factors.[24–26] It is becoming increasingly clear that investments in team science are not uniformly cost effective, although they can be enormously valuable under the right circumstances (e.g., the cross-disciplinary collaboration of Watson and Crick on the structure of DNA, the Kennedy Administration's commitment to land a crew on the moon by 1969).[27,28]

From the School of Social Ecology, University of California Irvine (Stokols, Misra), Irvine, California; the Division of Cancer Control and Population Sciences (Moser, Hall), National Cancer Institute, and the Office of Portfolio Analysis and Strategic Initiatives, NIH (Taylor), Bethesda, Maryland

Address correspondence and reprint requests to: Daniel Stokols, PhD, Department of Planning, Policy and Design, UC Irvine, 206-C Social Ecology 1 Building, School of Social Ecology, Irvine CA 92697. E-mail: dstokols@uci.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.003

Considering the varying levels of effectiveness that have been achieved by transdisciplinary teams and research centers within the health sciences, it is important to better understand the contextual determinants of collaborative success as a basis for knowing when (and when not) to invest in large-scale team science initiatives.[29] In short, investments in transdisciplinary team science and training must become more strategic and cost effective in the coming years, especially in light of recent budget cuts, resource shortages, and the importance of ensuring that research investments will yield scientific and translational advances that directly ameliorate population health and environmental problems at national and global levels.[30]

Mapping the Ecology of Team Science

To establish a more-strategic basis for designing, managing, and evaluating team science initiatives (and deciding when to opt instead for smaller-scale, unidisciplinary approaches to health problems), this review examines the ecology of team science, or the complex web of intrapersonal, interpersonal, organizational, institutional, physical environmental, technologic (e.g., cyber), and other political and societal factors that influence the effectiveness of transdisciplinary collaboration in research, training, clinical, and public-policy settings. This ecologic analysis suggests a typology of contextual circumstances that jointly determine the effectiveness of transdisciplinary science and training. A key implication of the proposed typology is that investments in team science should be strategically targeted toward those research questions, settings, and teams that are most conducive to the collaborative success and long-term cost effectiveness of transdisciplinary initiatives.[31]

Identifying the most appropriate criteria for judging the effectiveness of transdisciplinary team science initiatives depends, of course, on the ways in which key dimensions of team performance and the essential qualities of transdisciplinary collaboration are defined. For instance, in the fields of social psychology and organizational behavior, the effectiveness of a team's performance is typically defined in terms of the quantity and quality of team products; the affective, behavioral, and cognitive influences a transdisciplinary team has on its members; and the team's capacity to perform effectively in the future.[32] Yet the evaluation of team science initiatives (defined as a unique form of intellectual teamwork) generally impose additional criteria of success. For instance, Rosenfield[33] contends that a *sine qua non* of effective transdisciplinary collaboration is the development of shared conceptual frameworks that integrate and transcend the multiple disciplinary perspectives represented among team members. Moreover, transdisciplinary conceptual frameworks are characterized as reflecting a higher degree of integration than is achieved through interdisciplinary collaboration.[34–36] The least-integrative forms of cross-disciplinary research, according to Rosenfield,[33] are multidisciplinary projects in which participating scholars remain conceptually and methodologically anchored in their respective fields (although by definition some sharing of diverse perspectives also occurs in multidisciplinary research).

In contrast to Rosenfield's definition of transdisciplinarity, the NIH Roadmap initiative[4] treats the terms *interdisciplinary* and *transdisciplinary* as basically equivalent and, for simplicity, focuses on the promotion of interdisciplinary collaboration. Within the Roadmap initiative, interdisciplinary research is defined as that which ". . . integrates the analytical strengths of two or more often disparate disciplines to create a new hybrid discipline."[4] Examples of hybrid fields spawned by interdisciplinary health research are cognitive neuroscience, behavioral medicine, psychoneuroimmunology, bioinformatics, pharmacogenetics, proteomics, nanotechnology, and populomics.[37,38]

In the ensuing discussion, the distinctions among multidisciplinarity, interdisciplinarity, and transdisciplinarity posited by Rosenfield and endorsed by others are retained, because these terms define collaborative effectiveness along a continuum of scientific achievements rather than in terms of a dichotomy between the emergence or non-emergence of a hybrid scientific field.[13,14,21,36,39] For example, the development of a shared conceptual framework among members of a transdisciplinary research center can be viewed as an important, albeit incremental, collaborative milestone, even if it is only one of many intellectual precursors that eventually cumulate in the form of a newly recognized hybrid field. If the effectiveness of team science were defined solely in terms of the emergence of new hybrid fields, then many near- and mid-term collaborative scientific achievements would remain undetected in the evaluation of team initiatives. Thus, it is important to account for the temporal sequence of transdisciplinary collaborative outcomes (e.g., from the early development of integrative conceptual frameworks to the subsequent emergence of new hybrid scientific fields) in the evaluation of team science initiatives.

Generic and Project-Specific Criteria for Gauging the Effectiveness of Transdisciplinary Collaborations

The contrasting definitions of cross-disciplinary research (e.g., multidisciplinarity, interdisciplinarity, and transdisciplinarity) presented by Rosenfield and the NIH Roadmap initiative (and the alternative criteria for judging the effectiveness of transdisciplinary collaborations) are generic in the sense that they are intended to apply to broad categories of similarly organized initiatives and programs (e.g., National Cancer Institute transdisciplinary research and training centers). However, when diverse team science programs are compared, it becomes apparent that they often assign different priorities among the multiple potential outcomes of transdisciplinary collaboration. For instance, team science initiatives such as the NIH Clinical Translational Research Centers and the Centers for Population Health and Health Disparities emphasize strategies of community-based participatory research (as well as basic medical and behavioral research) for achieving effective collaboration among university researchers and community-based health practitioners as they work together to design and implement evidence-based disease-prevention programs.[30,40,41] Other team science initiatives, however, place less emphasis on the translation of scientific research into clinical practices and give higher priority to scientific discovery and intellectual integration. Thus, in addition to considering the generic criteria of transdisciplinary collaborative success, it is also essential that the evaluation of team science programs take into account their diverse, project-specific goals, ranging from the achievement of scientific advances and the education of transdisciplinary scholars to the translational, clinical, and public-policy benefits that accrue from investments in transdisciplinary research and training. To be maximally useful, the evaluation of team science initiatives should incorporate metrics that give the greatest weighting to the highest-priority goals (e.g., scientific, training, translational, policy) specified at the outset of each initiative by major stakeholder groups (e.g., funding agencies, principal investigators, community organizations, elected officials).[17,29]

At the same time, the content and priority ranking of collaborative goals may change over the life course of an initiative. For instance, the initial stage of a team science project may give the greatest emphasis to basic research and training, whereas the intermediate and long-term phases of collaboration may assign greater importance to the translation of scientific knowledge into community interventions and policies designed to improve public health. Thus, the substance and relative importance of an initiative's major goals may be phase-specific.

Clearly, any discussion of the ecology of team science must address the complexities inherent in selecting criteria for gauging the effectiveness of transdisciplinary collaboration, including those mentioned above. The typology of factors that influence the effectiveness of team science, presented in a later section of this paper, recognizes that the definition of effectiveness and the identification of highest-priority goals will vary somewhat among different research and training programs and across their different phases, and that the design, management, and evaluation of transdisciplinary initiatives must be tailored to address the unique and highest-priority goals of each. Moreover, multiple stakeholder groups (e.g., researchers, funders, community members) may define the highest-priority goals of a transdisciplinary program differently, thereby creating yet another challenge to the design, management, and evaluation of team science initiatives, as discussed below.

Review of Empirical Research on Team Performance and Transdisciplinary Collaboration

This analysis of contextual factors that influence the success of transdisciplinary collaborations is guided by empirical evidence drawn from at least four areas of scientific research: (1) social psychological and management research on the effectiveness of teams in organizational and institutional settings; (2) studies of cyber-infrastructures (i.e., computer-based infrastructures) designed to support transdisciplinary scientific collaboration; (3) field investigations of community-based coalitions for disease prevention and health promotion; and (4) studies focusing explicitly on the antecedents, processes, and outcomes of effective collaboration within transdisciplinary research centers and training programs. These areas were selected for review because they all identify key factors that facilitate or constrain teamwork across a variety of institutional and community settings. At the same time, the four research domains differ from each other in certain conceptual and methodologic respects. For instance, social psychological studies of team performance have relied heavily on short-term, laboratory-experimental investigations of randomly composed groups, whereas those in the fields of organizational behavior and management science more often have employed longitudinal field research to evaluate the functioning of pre-existing teams in corporate and other naturalistic settings.[32,42–44] Also, the criteria used to assess collaborative effectiveness vary widely, depending on whether the groups under study are randomly assembled and instructed to work on short-term experimental tasks or are longer-standing, self-selected teams employed by ongoing organizations to achieve specified financial, health, or intellectual outcomes.[45] Thus, university–community coalitions collaborate to promote population health, improvements in environmental quality, and social justice within a local community, whereas transdisciplinary science and training programs often place greater emphasis on intellectual discovery and scientific advancement as the most-highly prized collaborative outcomes.[29]

The four research domains reviewed below vary not only in terms of the kinds of teamwork studied within each, but also in the breadth or scope of collaboration examined in each field. Cross-disciplinary collaborations can be compared on at least three dimensions of integrative scope: organizational, geographic, and analytic, each ranging from narrow to broad.[29] The organizational scope of transdisciplinary collaboration includes **intra-organizational partnerships** in which participants work together within a single organization; **inter-organizational alliances** whose participants span multiple organizations; and **intersectoral partnerships** in which members representing multiple communities, regions, or nations form alliances to develop programs or policies covering larger geographic and political domains. For instance, studies of team performance in the fields of social psychology, organizational behavior, and management science predominantly emphasize an intra-organizational perspective, whereas research on university–community coalitions for health promotion encompass inter-organizational and intersectoral contexts of collaboration.

Similarly, the geographic scope of transdisciplinary collaboration ranges from local groups to community, regional, and national/global contexts of collaboration. Scientific teams, for example, include those based solely at a single locale (e.g., a university or research institute) as well as those whose participants collaborate across multiple, dispersed locations, often using electronic support systems to facilitate their communication.[46]

Finally, the analytic scope of transdisciplinary collaboration ranges from molecular (e.g., neuroscience) to molar (e.g., public policy) levels of intellectual analysis, depending on the nature of the scientific or community problems addressed by the team. As intellectual analyses move from molecular or cellular levels to community and policy perspectives, a wider range of academic and professional vantage points must be bridged to achieve a transdisciplinary approach to the problems at hand.[26] Generally, transdisciplinary collaborations encompassing broader organizational, geographic, and analytic scope face a larger and more complex array of potential coordination constraints as they pursue their scientific and community problem-solving goals.[29]

Differences in the kinds and scope of transdisciplinary collaborations studied within diverse fields suggest that extrapolations among the findings reported in each domain must be drawn with caution. A major goal underlying this analysis of transdisciplinary collaboration is to develop a typology of circumstances that constrain or enhance the effectiveness of team science and training programs. When the relevance of findings from social psychological and management studies of team performance for understanding transdisciplinary science initiatives are considered, for example, it is important to remain mindful of the differences between experimental teams studied in laboratory settings, on the one hand, and community-based coalitions and research organizations examined through naturalistic field research, on the other; or between assemblages of independent-minded scientists working in university settings compared to members of corporate teams that report directly to a single company boss. Nonetheless, certain contextual factors are consistently identified as important correlates or determinants of collaborative success across several research areas, as noted below. In this paper, particular attention is paid to these widely observed, high-leverage variables in developing a typology of contextual factors that influence the effectiveness of transdisciplinary collaborations. With those caveats, a review of empirical evidence drawn from four relevant research domains begins below.

Social Psychology and Management Research on the Effectiveness of Teams

Experimental studies of group dynamics and interpersonal processes (e.g., leadership, conformity, conflict) conducted in laboratory settings have been a focal area of social psychological research over the past six decades.[42–44,47,48] As concerns have grown in recent years about improving collaboration among members of community-based organizations, field research on teams working in and across specific organizational settings has expanded as a basis for better understanding how successful teams[a] work and what factors determine their effectiveness, such as team members' familiarity with each other, their social cohesiveness, group size, and leadership styles.[50–52] Empirical findings from this research are outlined below. Although the relevant literature is quite extensive, space constraints necessitate that the review of this earlier work be selective rather than exhaustive.

Team Members' Familiarity and Social Cohesiveness

Recent reviews of research on team effectiveness suggest that increased familiarity among team members as well as greater social cohesiveness lead to increased productivity.[32,45] Relatedly, it has been observed that social cohesiveness is enhanced in part by good performance itself.[45] In many organizational settings, strong network ties are more likely to form among members who share similarities in various demographic and educational criteria than among those who do not.[53]

[a]It is noted that distinctions have been drawn in social psychological and management research between the terms teams, groups, task forces, and their various subcategories (e.g., project teams, top management teams, production teams, action/involvement teams). However, these differences are not essential for purposes of this discussion, because all of the terms refer similarly to collections of interdependent individuals who share responsibility for outcomes and are recognized as distinct social entities by their members and outsiders. Moreover, because this study's purpose is to review the literature across disparate fields and to establish emergent themes relevant to transdisciplinary collaboration, the term *team* will be applied to all forms of collaboration examined in social psychology and management research.

Some studies have found that homogenous teams, although more socially cohesive, do not perform as well as heterogeneous teams on certain kinds of tasks, especially on creative and intellectual tasks.[54–56] Katz observed that familiarity among team members had a negative effect on team performance with the passage of time, suggesting that temporal factors play a crucial role in members' efforts to establish and sustain high levels of performance.[32,57] A recent experimental study assessed the effect of time on team performance under two conditions—one in which members were familiar with each other and another in which they were not—and found that, over time, initially unfamiliar team members performed just as well as the other team whose members were more familiar with each other at the outset.[58]

One explanation of the declining performance of teams whose members are familiar with each other is that, as familiar group members become more cohesive over time, interpersonal processes that diminish performance, such as social loafing[b] and "groupthink,"[c] intensify as well.[60–62] Another explanation is that communication among members declines as teams age.[57] Okhuysen[63] found that familiar teams exhibit less flexibility for change compared to teams of strangers, thereby jeopardizing their performance. Teams that are able to adapt to fluctuating task demands are more likely to be effective, because these environmental challenges prompt members to evaluate their current strategies and abandon ineffective ones.[64] Familiarity, however, may lock members into ineffective strategies over time because of their reluctance to modify pre-established roles and patterns of interaction.[63] Convergent evidence for the inverse link between familiarity and performance over time emerged from a field investigation of interdisciplinary scientific networks,[1] a topic discussed more fully in a later section.

Team Size and Physical Environmental Conditions

The effects of team size on performance are mixed, with some studies indicating that large teams require more coordination and time to reach decisions,[65] and others finding that teams, even with as many as 30–40 members, can achieve higher levels of performance because of their access to greater resources—especially time, energy, money, and expertise—for task completion.[49,66] Stewart's meta-analysis[67] examined empirical links between differences in team size and performance levels among teams working on complex tasks in uncertain environments and found a small but positive effect of team size on performance.

However, another study[68] of 15 interdisciplinary treatment teams in a hospital setting (where group sizes ranged from 5 to 12 members) found that overall effectiveness, measured by cohesiveness, meeting hospital standards, and the personal well-being of team members, was greater among smaller teams. That study also found that high levels of interdisciplinary collaboration were linked to greater cohesiveness which, in turn, contributed to improved performance. Moreover, members' ratings of physical environmental conditions at work, such as the availability of quiet and comfortable places for team meetings and adequate materials for discussion, were positively related to reported levels of interdisciplinary collaboration. The influence of a team's physical environment on patterns of collaboration also has been observed in earlier studies of corporate teams and university-based research centers.[13,26,69–71]

It is important to note that the optimal team size for enhanced performance is likely to vary, depending on the kinds of teams and organizations under study. For example, in a study of interdisciplinary research and training centers, Rhoten[25] found that smaller (<20 investigators) and medium-sized (21–50 members) centers were more conducive to the generation of interdisciplinary knowledge than larger centers (>50 investigators). Yet in other settings such as corporate departments, 20-member teams may be regarded as large rather than small. The relationships between membership size and performance quality thus are conditioned by the unique goals of particular teams and the ecologic contexts in which they function.

Leadership Traits and Behaviors

Earlier studies[17,29,72] of transdisciplinary research centers and teams suggest that leaders substantially influence collaborative processes and outcomes. Yet empirical links between the specific traits and behaviors of leaders and the effectiveness of team science initiatives remain to be drawn. There is, however, a long tradition of research on leadership, group performance, and organizational effectiveness within social psychology and management science, some of which is rooted in Max Weber's conceptualization of charismatic leaders.[73] For instance, research in these fields has identified various personal traits, such as intelligence, self-confidence, physical appearance, educational status, task-relevant knowledge, and sensitivity to members' socio-emotional needs, that contribute to effective leadership in team situations.[74–77]

[b]In the social psychology of groups, the social-loafing effect has been defined as a situation in which people expend less effort when working in groups than when working alone. One explanation is that people can get away with poor performance in groups because their individual outputs are not identifiable. Another is that they expect the other group members to loaf, and therefore lessen their own efforts to establish an equitable division of labor.[59]

[c]When group members try to reach consensus or minimize conflict without critically analyzing and evaluating ideas, either to avoid angering other group members or avoid being seen as foolish, they are exhibiting *groupthink*.[60]

Recent studies have moved beyond analyses of specific leadership traits toward a broader focus on the combinations of skills, patterns of behavior, and interpersonal styles exhibited by exemplary leaders.[78,79] According to Collins,[80] for example, it is the paradoxical blend of personal humility and strong professional will that enables some individuals to become exemplary leaders. Bennis[52] suggests that the leaders of "great groups" excel at generating and sustaining trust; cultivating a shared dream among members that provides them with direction, meaning, and hope; and have a bias toward risk taking and action. Similarly, the term *transformational leader* has been used in other studies[50,67,81] to describe individuals who are able to enhance fellow-members' motivation and performance by offering them a strong vision of collective success, bringing out the best in each member and empowering her or him to reach personally and collectively important goals. Teams rated higher on transformational leadership see themselves as more potent and achieve higher levels of performance.[81]

An important direction for future research is to examine the contextual influences on leaders' effectiveness within complex team science initiatives. As the organizational and geographic scope of transdisciplinary collaboration increases (e.g., for multisite initiatives), leadership responsibilities often must be shared and coordinated among multiple directors (e.g., those having primary responsibility for scientific, financial, and administrative leadership) located at geographically dispersed sites[29,72]—a topic discussed further in a later section of this review.

Participatory Goal Setting and Communication Patterns

Participatory goal setting is thought to enhance team performance by encouraging feelings of inclusiveness among team members and providing them structure, connection, and shared beliefs, as well as enhancing collective efficacy.[45,61,82–84] Importantly, the presence of a goal, compared to no goal or ill-defined goals, tends to elevate team performance by raising member effort and stimulating communication and cooperation.[32] Team-development strategies such as experiential learning and appreciative inquiry have been found to be useful in facilitating members' efforts to reach consensus about shared goals and aspirations.[50,61,85,86]

Communication has been a topic of long-standing interest in research on group dynamics. The lack of adequate feedback and communication is a major impediment to effective team performance.[61,86] Regular group communication involving the exchange of organization-relevant knowledge among employees was found to enhance innovation in a longitudinal study of manufacturing firms.[87] Good communication among team members encourages feelings of trust and psychological safety,[88] and enables teams to better manage issues of size, compatibility, and cohesion.[61] In a study of new-product team managers in a high-technology firm, Ancona and Caldwell[89] demonstrated that not only internal communication (communication among team members) but also external communication (communication beyond the teams) enhances performance. The use of group brainstorming to promote communication and idea generation also has received support, especially for teams communicating electronically.[32,45,46] The issue of effective communication for remote collaboration is discussed further in the section on electronic communication among spatially dispersed teams.[46,90]

Task and Outcome Interdependence

An additional factor that has been shown to influence team performance is the structural interdependence of members' tasks and rewards. An example of an interdependent task is software development, which requires a team consisting of programmers, quality-assurance experts, business analysts, and project managers to accomplish the task. An interdependent reward system is one in which all members are assessed and rewarded equally based on the performance of the team, regardless of variations in individual excellence. When researchers work collaboratively on a shared enterprise but pursue part of the project independently, they are said to be a *hybrid* team. Accordingly, members tasks and rewards have both individual and collective elements.[91]

In a study[91] of 150 teams of technicians in a corporation, it was found that teams perform best when their tasks and outcomes are either purely group-oriented or purely individual-oriented. Higher levels of task interdependence resulted in higher levels of cooperation, helping, and learning behavior, and demonstrated high-quality social processes. Similarly, group-reward systems for highly interdependent teams motivated members to perform well and resulted in greater effort. Hybrid teams, however, performed poorly, exhibited poor interpersonal processes, and had low levels of member satisfaction.[91]

These findings pose implications for the design of transdisciplinary research collaborations, notwithstanding the differences between corporate and scientific settings. Because transdisciplinary team science requires a high level of cooperation to achieve knowledge integration across disciplinary boundaries, it would seem advisable to organize research tasks so that they are structurally interdependent; encourage sustained collaboration through institutional, environmental, and technologic supports; and reward collaborative processes and achievements through an interdependent incentive system. Organizational structures that have hybrid or very low levels of interdependence have been shown to produce low levels of interaction among members and to prevent the development of collective norms and mutual learning.[92] At the same time, excessive structural interdependence in research settings, especially when not supported by organizational, environmental, and technologic resources, can become problematic, as much time and effort must be spent on coordination issues rather than on the task itself. To be maximally effective, team science initiatives may require a balance between interdependent task and reward structures on the one hand, and opportunities for autonomous or semi-autonomous teamwork on the other.[67,78,93]

Team Effectiveness in Remote Collaboration

Remote collaboration refers to those arrangements in which team members are geographically dispersed. Spatially (and often temporally and culturally) separated teams of workers collaborate on scientific or managerial projects through the Internet and by using other information and communication technologies. New terms such as *scientific collaboratories* (the terms *virtual teams* and *distributed collaboration* are also found in the literature)[46] have come to represent network-based facilities and organizational entities that span large distances to allow contact among researchers, access to data and instruments, and the sustained interaction required to accomplish research tasks.[94–96] Remote collaboration can be intra- or inter-organizational as well as intersectoral in scope, depending on the particular context of collaboration and its specific purpose. The geographic scale of remote collaboration may be quite broad, as members often communicate with partners located in other countries. Distributed collaboration poses unique challenges for team effectiveness. A small but steadily growing body of work has examined the conditions that facilitate and constrain the performance of spatially and temporally dispersed teams. These facilitative and constraining factors are categorized as technologic, environmental, socio-cognitive, and emotional.

Technologic Factors

The availability of adequate infrastructure—such as the requisite bandwidth for distance technology tools (e.g., digital video and high-quality audio); state-of-the-art workstations; and the availability of technical support—is critical to the scientific and managerial success of distance collaboration. Olson and Olson,[90] for example, describe how a team of manufacturing engineers in Europe encountered difficulties while explaining a manufacturing issue to design engineers in the U.S. because they used only audio technology rather than both audio and video. The high costs and increased expenditure of time required to initiate and synchronize applications like data conferencing often curtail their use (e.g., broadcasting slides only briefly and reducing collaboration over joint work).[97] Because scientific and managerial collaborations require the transfer of large amounts of data securely and quickly, even synchronously, the additional challenges of maintaining data security, integrity, privacy, and long-term archival access often arise.[72]

Apart from these technologic infrastructure-readiness factors, conditions of technology readiness also have been addressed.[90] Observational studies of scientific and industrial collaboratories have found that users unfamiliar or inexperienced with the use of advanced technologies are not prepared for such forms of collaboration. Technology readiness also requires users to have adapted to the habits and patterns of technology use, such as preparing for and setting up meetings, having regular access to technology, and making information accessible to others in a timely fashion.[90] Assessing the technology readiness of participants before implementing distance collaboration is crucial for ensuring its success.

Environmental Factors

Technology-mediated collaboration changes the way people interact with their socio-physical surroundings. Tacit behaviors taken for granted in face-to-face transactions become major impediments in remote collaboration. Teams using tools for audio conferencing, video conferencing, or both, encounter difficulties such as being unaware of other participants' identities, the topic of discussion, the identity of speakers, and the mental and emotional states of their remotely located partners.[90] Distance collaborators must adapt to the loss of shared physical settings and socio-spatial cues. For instance, it becomes critical for dispersed team members to be explicit about information that is normally tacit in collocated teams to ease the collaborative process.[98] Another adjustment that may facilitate remote collaboration is the use of technology-mediated communication only for unambiguous activities that do not require frequent interaction and feedback (e.g., data collection versus idea generation or designing).[90,98]

An additional constraint faced by virtual teams, especially in international collaboration, is working in different time zones.[99] If coordinated well, work could proceed 24 hours a day, leading to increased productivity. However, working across multiple time zones means that team members are in different stages of their circadian rhythms—members of the U.S. team, for example, could be groggy early in the morning while simultaneously their French collaborators would be alert in the late afternoon.[90] Managing cultural differences poses other challenges for global teams. Misunderstandings due to linguistic differences, disparities in management styles, and status conventions in different cultures can constrain the effectiveness of global teams.[90]

Socio-Cognitive and Emotional Factors

Building and sustaining trust are perhaps the most crucial conditions virtual teams must achieve to be successful. Trust is especially fragile and transient in virtual teams, as members do not share a common socio-physical context, norms, values, or expectations, nor do they have opportunities to monitor each other's behavior.[100,101] An experimental study of computer-mediated teamwork found that lack of trust is a major constraint on performance, especially when teams engage in risky activities and have few shared experiences to rely on. Initial face-to-face contact and socialization were found to increase the trust levels among team members, facilitate the formation of social norms, and aid the establishment of group identity.[102] Face-to-face contact early-on may be a prerequisite for successful remote collaboration.

Effective and sustained communication among geographically isolated team members emerges as another essential element for creating common ground as a precursor to trust among collaborators.[90] Jarvenpaa and Leidner[100] found that increased social communication, along with task-related communication, strengthens trust. Communication expressing enthusiasm and optimism explicitly was found to facilitate the establishment of trust early-on in a collaboration. Teams that had high levels of trust exchanged many messages for clarification and to garner consensus on the task. They also initiated more communication and provided timely substantive feedback to fellow members. Enthusiastic and motivated leadership was another key factor that differentiated high-trust from low-trust virtual teams.[100]

Specific interventions found to improve distance collaboration include the presence of a technology facilitator to help resolve technical problems and a virtual-meeting facilitator who mediated discussions among the remote parties.[90,97] When multiple locations are involved, the presence of a site coordinator to handle location-specific administrative issues was found to improve communication among parties.[103] The creation of formalized communication conventions might include protocols for turn taking and the use of common specialized vocabulary among sites.[90] In addition to organizational strategies for improving interaction among dispersed team members, technologic advances also can ease some of the difficulties inherent in remote collaboration. For instance, technologically enabled group performance support systems, including tools for electronic brainstorming, evaluation, and voting, as well as exchanging comments, can assist virtual teams with decision making, resource planning, and other collaborative activities.[104]

Remote collaboration creates new expectations, alters roles, and shifts communication patterns for its members.[98] It therefore requires participants to make various social, organizational, and physical environmental adjustments and adaptations to new tools and technologies.[105] The success of both collocated and virtual teams is likely to be influenced by the collaboration readiness of its members and participating organizations.[26,90] Organizations and teams that lack a culture of sharing and collaboration are likely to resist change and remain ineffective. Moreover, if incentive structures are not aligned to encourage the adoption of collaborative tools and related behaviors, such behaviors are not likely to occur. Finholt[98] suggests that team members establish formal conventions about how data are to be used and credit shared at the outset of their collaboration to enhance its effectiveness. Another activity that can facilitate remote teamwork is the longitudinal evaluation of collaborative processes and outcomes (e.g., Teasley and Wolinsky[106]). Formative evaluations can lead to refinements in research and training programs, strengthen social networks, and encourage new organizational forms to emerge.[26,94,106]

Team Effectiveness in Community Coalitions

Community coalitions between scientists and practitioners translate scientific findings into interventions and programs that promote public health and social justice. These collaborations are usually inter-organizational in scope. The scale and complexity of transdisciplinary collaboration among researchers and practitioners increase further as the goals become broader-gauged with the design, implementation, and evaluation of health programs and policies spanning local, regional, national, and international levels. Such broad-gauged collaborations are intersectoral in scope.[29] Community coalitions are prone to the difficulties inherent in teamwork (such as conflict and social fragmentation) because of the complexity of their goals and environmental contexts as well as the diversity of participants' world views and educational backgrounds. Factors that can facilitate or constrain the effectiveness of community coalitions are noted below.

Identification of Common Goals and Outcomes

Contributing to both community concerns and research goals is a defining feature of transdisciplinary action research. Citizen groups, practitioners, and researchers bring diverse and often competing interests and problem-solving agendas to their partnerships.[29] At times, the expectations and priorities of funding agencies are different from a coalition's goals, imposing additional collaborative constraints.[107,108] An evaluation of the first 4 years of an intersectoral community coalition identified as a key challenge the achieving of a balance between community interests and research needs.[108] Whereas practitioners' goals are more pragmatic, community-oriented, and favorably disposed to quick decisions and the implementation of problem-solving strategies, researchers generally have a longer-term orientation, are more concerned with basic research questions, and aspire to publication and the receipt of grant funds.[29,107] Conflicts also may arise from differences in ethical practices and beliefs about what constitutes a realistic timeline to achieve the coalition's goals.[72] Coalitions whose members endorse competing goals and outcomes; hold different views of science and society; and use dissimilar terminology, language, and decision-making styles are likely to experience conflicts that undermine the team's performance. Coalitions that identify clear goals and objectives perceived to be attainable, agree on shared research-principles, and reach consensus on major areas of concern face fewer collaborative challenges.[29,107–109]

Distribution of Power and Control

The inequitable distribution of resources (e.g., information, time, funding, decision-making power, participation, and control over aspects of the community problem-solving process) is a major impediment to coalition progress and sustainability. Perceived status differences— between scientists and practitioners, and between health professionals and community members— can prevent collaborations from achieving their goals.[29,107–110] Other studies of coalitions highlight the importance of the continuity of collaboration between researchers and practitioners over extended periods and across the various phases of action–research, including the formulation of goals and the translation of research into preventive and therapeutic interventions, scientific publication, and community empowerment.[29,108,111] The joint development of operating norms that encourage open communication, mutual respect, inclusiveness, and shared decision making also facilitate the collaborative process.[107,108]

History of Collaboration

Building on prior positive experiences with a certain organization or community enhances trust among coalition partners and is a practical strategy for strengthening future collaborations. A lack of trust and respect arise from prior collaborations in which community members perceived no direct benefit or even harm, or if they received no feedback.[107,112] Groups in the U.S. that have experienced historic oppression, such as Native American and African-American communities, may mistrust scientists. Scientists, on the other hand, may not be aware of such feelings of mistrust when formulating research goals and planning tasks that require the involvement of these communities.[111] Also, the simple lack of experience in working with a particular organization or conducting community-based research can result in a considerable amount of time being spent to establish trust and define shared principles of collaboration.[108] Prior experience in working with partners and conducting transdisciplinary action–research eases these pressures considerably.[40]

Leadership and Member Characteristics

Leaders who are supportive, democratic, empowering, and committed and who encourage cooperation and engage the support of others significantly enhance transdisciplinary collaborations within both university and community settings.[29,107–109,113] Kumpfer and colleagues[113] conducted an exploratory study to test the relationship of leadership style to team effectiveness in an alcohol and drug abuse–prevention coalition. An empowering leadership style was found to boost member satisfaction and team efficacy, and was critical to the implementation and maintenance stages of the coalition as well as to its outcomes. Because coalitions are prone to internal disagreements, leaders adept at handling conflict are a valuable asset. By contrast, those who foster secrecy, in-group exclusiveness, and confrontation can weaken cooperative problem solving among members and minimize their use of intellectual resources. In inter-organizational and intersectoral coalitions, the presence of multiple program champions who are well-known and respected among partners can facilitate coordination across participating organizations.[109,112]

Members' readiness for collaboration also influences the outcomes of the community coalition. Collaboration-readiness factors include the sharing of a transdisciplinary ethic by coalition members and are expressed by their methodologic flexibility, cooperative spirit, inclusiveness, and positive attitudes toward collaboration.[107,109,114] In addition to their skills in research design and methods, members should be skilled in group processes, team development, negotiation, conflict resolution, and interpersonal communication.[107] Regular and unconstrained communication among team members—interpersonal as well as project-related—is a necessary condition to establish and maintain trust among members, provide clarity about coalition goals and member roles, and resolve disagreements or conflicts. The provision of well-developed electronic communication systems also facilitates coordination among partners.[29,109]

Organizational Support

A challenge faced by community coalitions is the decline in participation or involvement by members due to circumstances such as lack of time, scarce resources, insufficient appreciation or recognition, competing institutional demands, loss of autonomy in decision making, frustration due to lack of progress, and interpersonal conflict.[107–109] Sustaining community coalitions requires that members' incentives to remain involved exceed the personal costs they incur through their participation. Examples of such incentives are financial compensation, training and educational opportunities, and peer recognition.[107] Broad-based institutional support for transdisciplinary collaboration (e.g., changes in tenure and promotion policies in universities) and rewards for community-based research (e.g., the publication of findings in respected journals) may increase the collaboration readiness of researchers and practitioners alike. Finally, assurances of long-term funding by public agencies and private foundations also enable coalition members to build sustainable partnerships.[29,107,108]

Studies of Transdisciplinary Science and Training Programs

Research on the antecedents, processes, and outcomes of scientific collaboration in transdisciplinary research centers and teams has grown steadily since the mid-1990s. Detailed reviews of these studies are available elsewhere.[10,11,13,22,25] The existing literature on the science of team science consists primarily of qualitative case studies employing structured interviews, surveys, and observations of collaborative activities among researchers as they occur in offices and laboratories. Very few experimental or quasi-experimental studies of transdisciplinary collaboration in scientific and training settings have been published (see Sonnewald[115] for an exception to this trend), thereby precluding the possibility of determining causal relationships among key variables. Nonetheless, systematic assessments of collaborative processes and outcomes gained through comparative case studies of transdisciplinary science and training centers have yielded valuable insights about the contextual factors that facilitate or constrain intellectual integration spanning multiple fields. In this section, some of the major themes that have emerged from earlier studies of team science are summarized.

Tendencies Toward Conflict

Conflict and tensions among members of a transdisciplinary center or team stemming from divergent disciplinary world views, competing theoretical and methodologic perspectives, different departmental affiliations, and dissimilar interpersonal styles hinder the formulation of clear goals and their accomplishment.[1,29,39,116] While disagreements and conflict can contribute to knowledge construction, learning, and innovation,[117] it is important to negotiate these differences, as they can foster interpersonal tensions, social fragmentation and subgrouping, and non-overlapping (even competing) agendas; eventually they can undermine the collaboration's ability to meet its goals.[26,29] Overcoming such conflicts requires that members of a collaboration establish familiarity with each other's way of thinking. This is possible through the prolonged and regular exchange of ideas and the development of informal personal relationships.[117] Off-site retreats have been shown to promote communication among team members, reduce interdisciplinary tension, and stimulate intellectual integration.[26] Having common visions and goals, a strong motivation to achieve them,[29,72] and the will to make the collaboration successful[117] also help members to put their disagreements behind them and move forward. The leadership skills of center directors, especially tactfulness in conflict resolution and the ability to encourage cooperation among members, emerge as an important asset for the success of transdisciplinary teams.[29,39]

Collaboration Readiness

Collaborative-readiness factors (the presence or absence of institutional supports for interdepartmental and cross-disciplinary collaboration; the breadth of disciplines, departments, and institutions included in a particular center; the degree to which team members have worked with each other on other projects; the spatial proximity of the members' offices or laboratories; and the availability of electronic linkages for efficient communication) strongly influence the team's prospects for success.[11,13,17,27,29,90,118] Previous case studies assessing collaborative outcomes in research centers and teams suggest that the more these contextual factors are present at the outset of the collaboration, the better a team's prospects for achieving its collaborative goals.[26,119]

Preparation and Practice

The importance of preparation and practice for ensuring successful collaboration has been emphasized in prior evaluations of transdisciplinary centers and teams.[14,26] Unrealistic expectations for complete cooperation and harmony, along with ambiguity of goals and intended outcomes, can impede the team's collaborative efforts. Members must be aware of the collaborative constraints, disagreements, and conflicts that they are likely to encounter over the course of the project and be prepared to dedicate considerable time and effort toward establishing common ground both intellectually and socially.[10,11,21,27,120] Thus, transdisciplinary collaboration, to be effective, requires substantial preparation, practice, and sustained effort.[29]

Conceptualizing the Ecology of Transdisciplinary Team Science and Collaborative Effectiveness

The review of empirical literature on team performance presented in the preceding sections highlights the importance of certain factors, identified across multiple research domains, that either enhance or hinder the effectiveness of transdisciplinary collaborations. For example, the crucial roles played by exemplary leaders of transdisciplinary initiatives, the importance of establishing interpersonal trust and respect among team members, and the organizational and technologic aspects of collaboration readiness are among the most-commonly-cited factors that exert strong influences on transdisciplinary collaborative processes and outcomes. An overview of the major factors that facilitate or constrain transdisciplinary collaboration, identified in each of the four research domains reviewed above, is presented in Table 1. The facilitating and constraining influences on transdisciplinary collaboration listed there and derived from earlier studies of team performance provide an empirical and conceptual foundation for understanding the ecology of team science and establishing a typology of contextual factors that jointly determine the effectiveness of transdisciplinary research and training initiatives.

Although the indicators of team performance in transdisciplinary collaborations vary (depending on the scientific and community problems being addressed; the scale of the collaboration [intra-organizational, inter-organizational, or intersectoral]; and center-specific goals and desired outcomes), certain structural features are nonetheless common to all transdisciplinary projects. First, transdisciplinary teams are inherently diverse in their composition, are charged with complex and difficult tasks, and can function in dynamic and uncertain social environments. Second, transdisciplinary collaborations are likely to be hybrid in nature, such that certain tasks requiring high structural interdependence and coordination are combined with others performed independently. Rewards in academic settings, on the other hand, traditionally have been based on individual merit. Scientists' contributions to a field are generally evaluated in terms of their single- or co-authored publications. Third, transdisciplinary science teams in academia are likely to have a higher degree of autonomy compared to those working in corporations. Finally, many transdisciplinary collaborations include members who are geographically dispersed.

Earlier studies reveal the difficulties that teams can encounter with the abovementioned circumstances. Heterogeneous and hybrid teams often experience interpersonal tensions and social fragmentation.[53,91] The ambiguity of goals, outcomes, and tasks makes transdisciplinary teams susceptible to conflict.[29] Uncertainty and instability—arising from changes in membership and administration, institutional policies, funding limitations, and time pressure—decrease the psychological safety of members and make the establishment and maintenance of trust among members particularly challenging. Moreover, the contexts in which teams work change with time. How can these barriers to teamwork in transdisciplinary collaborations be overcome or diminished, so that team members can reach their intellectual potential? In the ensuing sections are outlined the major intrapersonal, interpersonal, organizational, physical environmental, technologic, and political and societal factors that influence the effectiveness of team science, based on the literature review presented earlier. A summary of these key factors situated at each level of analysis (i.e., intrapersonal through political and societal) is provided in Table 2.

Intrapersonal Factors

Individuals who value collaboration, support a culture of sharing, and embrace a transdisciplinary ethic are well-suited for transdisciplinary teams.[13,39,109] Members' collaborative readiness (gauged in terms of their preparedness for the uncertainties and complexities of transdisciplinary teamwork,[29] their methodologic flexibility,[107] their openness to disparate disciplinary perspectives and world views, and their willingness to devote substantial amounts of time both to learning about others' expertise and developing intellectual and personal relationships) appears to be crucial to the success of team science initiatives. The sharing of egalitarian values,[39] allegiance to ethical conduct and shared responsibility,[121] and enthusiasm for achieving collaborative goals further enhance the prospects of transdisciplinary success. Other important considerations are the extent of collaborative experience that team members have had with each other in the past and their experience with transdisciplinary collaboration in general. A history of positive collaboration increases members' readiness for effective teamwork because they share more common ground at the outset and thus may not have to spend as much time establishing and sustaining trust (compared to teams whose members begin collaborating with little or no history of working together on earlier projects).[26,29,107,108,118,119]

In addition to team members' characteristics, a team leader's style plays a pivotal role in ensuring collaborative success. The most effective leaders in collaborative settings are empowering, inclusive, and transformational in their style; skillful in negotiating and resolving conflicts; and generous in offering constructive feedback and encouragement to colleagues. Those skills enable them to bolster trust and cohesiveness among team members and to facilitate high levels of performance.[29,52,107,113] Moreover, dynamic leadership—

Table 1. Factors facilitating or constraining collaborative effectiveness identified in four areas of team research

Area	Facilitating factors	Constraining factors
Social psychology and organizational behavior	Social cohesiveness and familiarity among team members Flexibility to adapt to changing task requirements and environmental conditions Transformational and empowering leaders who have excellent tactical skills and are able to foster collaboration through their respectful and inclusive orientation toward team members Participatory group goal setting and decision making, encouraging active roles to be played by all members in reaching consensus on major goals and decisions Team development strategies such as experiential learning and appreciative inquiry to encourage members' active participation Regular and effective communication and feedback among members to foster trust Organizational support for members' diversity and heterogeneity, especially in intellectual and scientific endeavors Opportunities for face-to-face contact and relationship building Access to physical environment resources that support collaboration (e.g., comfortable meeting areas, distraction-free and private work spaces for individualized and small-group tasks that require close concentration or confidentiality) Members share egalitarian values and mutual respect among team members throughout all stages of collaboration	Groupthink and social loafing, sometimes arising from prolonged familiarity and rigid operating procedures Inflexibility in the face of changing task demands and environmental conditions Lack of adequate and regular communication and feedback, resulting in low levels of trust among members and social fragmentation Leaders whose styles are noncollaborative and exclusionary rather than collaborative and inclusive Too-small or too-large team size in relation to specific task requirements and collaborative goals Hybrid task and reward structures in which tasks require interdependent efforts among members but incentives are distributed on an individualistic and meritocratic basis Insufficient opportunities for face-to-face contact among members Failure to identify and utilize the resources of all group members Work environments that inhibit communication among team members, hinder privacy regulation, or are too distracting Noncollaborative rather than collaborative attitudes and values among team members
Cyber-infrastructures for remote collaboration	Technologic infrastructure readiness, including availability of adequate bandwidth, connectivity, and electronic communications equipment to support remote collaboration Collaboration readiness of team members and organizations (i.e., their willingness to share information cooperatively; the existence of incentives to participate in and sustain collaboration; and broad-based institutional, organizational, and administrative support) Technology readiness of users (i.e., their adaptation to habits and patterns of technology use such as familiarity with tools, making information accessible to others, providing regular and prompt feedback, and adequate preparation for meetings) Ample opportunities for face-to-face contact throughout all stages of remote collaboration Regular face-to-face meetings and socialization among remote team members to increase trust and to create and sustain group identity Sustained communication among members to establish common ground and reduce task-related uncertainties Enthusiastic leaders strongly committed to effective remote collaboration Creation of new roles and communication patterns that enhance distance collaboration	Lack of adequate technical infrastructure such as networking, bandwidth, technical support, and appropriate hardware and software Technologic concerns about speed, data security, integrity, privacy, and effective access and retrieval that render distance collaboration complex and challenging Constrained audio and visual choices and the use of media that are inappropriate for the task at hand Financial costs and expenditures of time and effort for establishing requisite infrastructure for distance collaboration Lack of experience and familiarity with the use of distance-collaboration tools Communication challenges in establishing team identity and trust due to the absence of shared physical settings along with nonverbal and spatial cues Absence of a culture of sharing information and non-alignment of reward structures to encourage collaboration and the use of collaboration tools

(continued on next page)

Table 1. Factors facilitating or constraining collaborative effectiveness identified in four areas of team research *(continued)*

Area	Facilitating factors	Constraining factors
Community coalitions among scientists and practitioners	Identification of common and clear goals, objectives, outcomes, and consensus among team members regarding their collaborative priorities Development of a shared statement of principles among coalition members and formalization of mutual benefits and responsibilities Continuity of collaboration throughout all phases of the coalition Joint development of operating norms that encourage open communication, inclusiveness, and shared decision making Prior positive experiences of collaboration with participating community organizations and their members Supportive, democratic, and empowering leaders who engage the participation of all members, encourage their cooperation, and are skilled in conflict resolution Members' readiness for collaboration, including their cooperative orientation, methodologic flexibility, positive attitudes toward collaboration, and interpersonal communications skills and training Presence of well-developed electronic communication systems to encourage and sustain collaboration among team members Strong incentives to participate and remain involved (e.g., financial, training and education, public recognition, tenure and promotion) Sustained support by funding agencies to enable the coalition to accomplish its major goals	Disagreement and conflicts due to divergent understandings of the coalition's goals and timelines among community practitioners and academic researchers Presence of unclear, ambiguous, and complex goals Conflicts arising from different scientific world views, disciplinary perspectives, and decision-making styles Inequitable distribution of decision-making power, information, time, resources, and control over the coalition's action–research activities Perception of status differences between scientists and community practitioners Lack of trust and respect arising from negative experiences in prior collaborative projects Leaders who encourage secrecy, in-group exclusiveness, and interpersonal competition and confrontation Absence of adequate and regular communication among members Decline of members' participation, involvement, or both, in coalition activities due to lack of time, personal costs, absence of strong incentives to participate, and competing institutional demands Uncertainties about and absence of sustained funding to support the coalition's long-term goals and activities
Evaluative studies of transdisciplinary research centers and training programs	Prior experience of positive collaboration with team members on earlier transdisciplinary projects Presence of a strong, shared vision; agreement on highest-priority goals and the timelines for achieving them Exemplary leadership skills of center directors, especially conflict-resolution skills and ability to encourage cooperation among members while easing tensions among divergent scientific world views and disciplinary perspectives Prolonged and regular exchange of ideas to encourage the development of positive and informal interpersonal relationships Presence of electronic systems (e.g., intranet and Internet sites) to facilitate regular communication among center members Spatial proximity of scientists' offices and laboratories Physical environments that afford opportunities for face-to-face contact among center members (e.g., comfortable, shared-meeting areas; distraction-free office and laboratory settings) Members' awareness of and preparation for the collaborative constraints, disagreements, and conflicts they are likely to encounter over the course of their collaboration; availability of training resources and negotiation strategies for resolving the tensions inherent in transdisciplinary research and training initiatives	Lack of experience among team members in working together on prior transdisciplinary research and training programs Lack of a shared vision among members about highest-priority goals and the timelines for achieving them Conflicts and tensions stemming from alternative disciplinary perspectives, multiple departmental affiliations, and contrasting interpersonal styles Lack of collaborative skills and management experience among available leaders Lack of both regular communication among team members and adequate cyber-infrastructure to support frequent and effective exchanges of information Absence of institutional supports and organizational incentives to sustain interdepartmental and inter-university collaboration Lack of physical environments (e.g., shared team-space) that encourage face-to-face contact among members of transdisciplinary research centers and training programs Lack of training programs to enhance team members' readiness for collaboration in transdisciplinary research and training activities; unrealistic expectations for complete cooperation and harmony among team members

Table 2. Key contextual factors that influence transdisciplinary team effectiveness at each level of analysis

Intrapersonal	Interpersonal	Organizational/institutional	Physical/environmental	Technologic	Sociopolitical
Members' attitudes and values during the formation of a transdisciplinary collaboration, such as valuing collaboration, supporting a culture of sharing, embracing a transdisciplinary ethic, and sharing egalitarian values Members' collaborative readiness in terms of their openness to other disciplinary perspectives; willingness to devote large amounts time and effort to building personal relationships; and preparedness for the uncertainties, tensions, and complexities inherent in transdisciplinary teamwork Members' collaborative experiences with each other on earlier projects Presence of exemplary leaders who are empowering, inclusive, and transformational; a participatory leadership style that enables all members to play an active role in team goal-setting and decision-making activities	Regular and effective social and intellectual communications to establish common ground, overcome task-related uncertainties, and develop consensus around a shared vision and collective goals Diversity of members' knowledge and skills Members' ability to learn about each other's expertise and create a hospitable conversational space Mutual respect among team members Members' familiarity and social cohesiveness, coupled with their ability to adapt flexibly to changing circumstances, remain open to new perspectives, and challenge existing assumptions and procedures	Presence of strong organizational incentives to encourage participation and sustain collaborative orientation among members Broad-based institutional support for intradepartmental and inter-university collaboration through modifications of organizational structures and administrative routines (e.g., merit and promotion procedures in academic settings) Nonhierarchic arrangements that provide autonomy to team members and encourage participatory goal setting and decision making Breadth of disciplinary perspectives represented among team members Scheduling of retreats and informal social events to encourage informal contact and communication among members Assurances of long-term support by funding agencies so that teams have more time to establish trust, build relationships, and accomplish their goals	Spatial proximity of team members' offices and laboratories to encourage informal contact and communication Availability of comfortable meeting areas for group discussion and brainstorming activities Access to distraction-free work spaces for individualized tasks requiring concentration, confidentiality, or both Physical environments that support members' efforts to regulate their interpersonal privacy and accessibility to others over the course of their collaboration	An organization's technologic infrastructure readiness, or access to necessary bandwidth, electronic networking capabilities, linkages between sites, and technical support for remote collaboration Provisions for high-level data security, integrity, privacy, rapid retrieval, and long-term archival access, and technologies that facilitate the formation of knowledge and social networks Members' technologic readiness, including their knowledge of and familiarity with various electronic information and communication tools, protocols, codes of conduct for distance collaboration, and the effectiveness of their communication styles	Easing of international tensions through cooperative policies that encourage exchanges of scientific information and transdisciplinary collaboration among scientists from different regions of the world Enacting policies and protocols to support effective transdisciplinary collaboration, such as those ensuring ethical scientific conduct and management of intellectual property ownership and licensing Occurrences of adverse global environmental changes and public health problems that prompt intersectoral and international transdisciplinary collaboration in scientific research and training programs

whereby members share authority and responsibility according to the shifting requirements of their tasks—lessens the pressures felt by single individuals while enabling all members to play an active role in team decision making and activities.[61]

Interpersonal Factors

Interpersonal communication has been found in earlier studies[1,13,26] to be a critical determinant of collaborative effectiveness. Because of the inherent diversity of transdisciplinary teams, regular and effective intellectual and social communications are necessary so members can clarify roles, task requirements, collective goals, and intended outcomes as well as learn about their colleagues, understand and respect their alternative perspectives, and eventually transcend disciplinary and departmental boundaries to develop novel conceptual frameworks for understanding and solving the problems under investigation. If members are to learn from each other as the team develops, build a shared identity and a hospitable conversational space, strengthen collaborative processes, and ease interdisciplinary tensions, they must be able to engage in ongoing, mutually respectful, and constructive communication. Such communication, by enabling them to develop a shared vision and articulate common goals and by encouraging positive imagery and appreciative inquiry, empowers them to surpass obstacles and achieve those goals.[85] Furthermore, it is important that members be able to adapt to changing circumstances and remain open to new perspectives, particularly as the team matures and becomes more cohesive. The capacity of team members to adapt to new situations and challenge their existing assumptions and procedures is a crucial ingredient of collaborative success.[60,63,64]

Organizational and Institutional Factors

A prerequisite for sustaining motivation among participants in team science initiatives is the presence of strong organizational incentives.[107,109] For instance, an important incentive for motivating junior researchers to participate actively in transdisciplinary research and training initiatives is greater recognition for collaborative work through changes in university tenure and promotion policies.[23,24] Institutional support for intradepartmental and inter-university collaboration can be increased through the modification of organizational structures and routines.[17] Nonhierarchic organizations that encourage participatory goal setting and decision making foster inclusiveness and more-effective collaboration. Assurances of long-term funding by public agencies and private foundations also provide team members more time to develop the relationships and trust so critical for collaborative success.

An organization's collaboration readiness—reflected in the extent of its collaborative activities, breadth of disciplines, culture of sharing information, equitable access to information and technology, preparation for meetings, and ample opportunities for brainstorming new ideas—contributes in important ways to effective collaboration.[29,90] Because team science projects require substantial time expenditure for group meetings and brainstorming sessions, participating organizations must recognize and reward members for engaging in collaborative activities by providing organizational, environmental, and technologic support and incentive structures.

Physical Environmental Factors

One strategy for encouraging communication, trust, and the integration of intellectual ideas is to maximize spatial proximity among members' offices and laboratories.[29] Where this arrangement is not feasible, it becomes important to schedule regular face-to-face meetings, social gatherings, retreats, and other opportunities for team members to meet and communicate. Earlier studies[29] also indicate that reduced spatial, temporal, and emotional cues in remote collaborations render interpersonal trust fragile, and are often associated with misunderstandings, conflict, and social fragmentation. Face-to-face contact prior to engaging in remote collaboration is essential in establishing some degree of trust at the outset of the project.[90] At the same time, earlier studies[69–71] of team environments suggest the importance of providing environmental support (e.g., access to distraction-free work spaces and comfortable meeting areas) to facilitate members' regulation of interpersonal privacy and their participation in both individualized tasks requiring high levels of concentration or confidentiality and collective activities involving group discussion and brainstorming.

Technologic Factors

Technologic readiness and technologic infrastructure readiness[90] strongly influence remote as well as place-based collaborations. The organization's technologic infrastructure readiness—access to necessary bandwidth, electronic-networking capabilities, linkages between sites, and technical support—is a vital component of successful transdisciplinary collaborations.[90] Providing data security, integrity, privacy, rapid retrieval, long-term archival access, and technologies that facilitate the formation of knowledge and social networks has been found to enhance remote scientific collaborations.[46,72] Members' technologic readiness, including their familiarity with various electronic information and communication tools, protocols, and codes of conduct as well as the effectiveness of their communication style, is directly related to the team's prospects for achieving its scientific goals through remote transdisciplinary collaboration.[90]

Political and Societal Factors

The easing of political barriers through cooperative international policies and the reduction of tensions between nations can encourage the initiation and longer-term success of transdisciplinary science collaborations.[28,122,123] At the same time, global environmental changes and health challenges have spawned large-scale international collaborations for scientific research and community health promotion, exemplified by the WHO's Healthy Cities Program.[124–126] At state and national policymaking levels, the enactment of protocols for ensuring ethical scientific conduct, adjudicating claims to intellectual property ownership and licensing, and protecting animal and human subjects' rights provide the legal foundations for conducting effective large-scale transdisciplinary collaborations.[72,127]

A diagrammatic representation of these broad categories of contextual influences on transdisciplinary research and training programs is provided in Figure 1. The multiple categories of contextual factors shown there provide a typology of key variables that influence the effectiveness of transdisciplinary collaborations, grouped according to the intrapersonal, interpersonal, organizational, institutional, physical environmental, technologic, and political and societal levels of analysis discussed above.

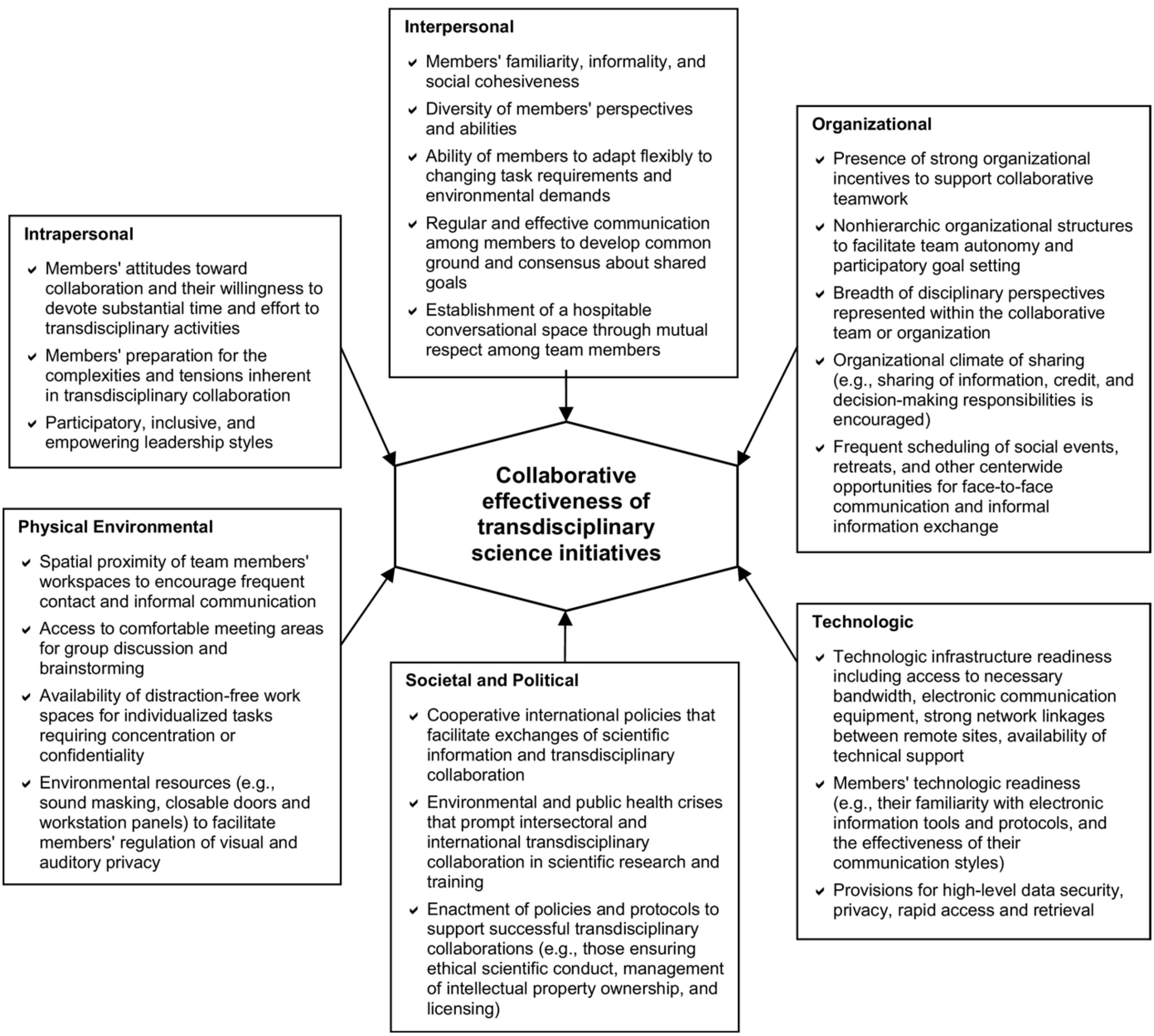


Figure 1. Typology of contextual factors influencing transdisciplinary scientific collaboration

Designing and Managing the Ecology of Team Science to Enhance Collaborative Effectiveness in Transdisciplinary Research and Training

This concluding section focuses on an important issue raised at the outset of the article—namely, the need to better understand the contextual determinants of collaborative success as a basis for making future investments in large-scale team science initiatives more strategic (i.e., scientifically productive and financially cost effective). Having reviewed the empirical evidence for contextual determinants of team performance across four distinct areas of research, this study addresses below the practical implications of that evidence for future efforts to enhance the success of transdisciplinary science initiatives.

The sheer diversity of transdisciplinary research and training programs (reflected in their different structural features, stated goals, and effectiveness criteria) suggests that the contextual factors most crucial for collaborative success will vary from one initiative to another. For example, having an adequate technologic infrastructure in place at remote sites is an essential prerequisite for effective distance collaboration but may not be as crucial for the members of a transdisciplinary team who work together at the same location.[46,90] Similarly, community-based program champions and multiple leaders representing different organizations enhance the effectiveness of inter-organizational and intersectoral transdisciplinary coalitions, but may not be necessary for the success of transdisciplinary research centers linked primarily to academic institutions.[112] Thus, there is no one-size-fits-all set of contextual factors that can be expected to exert the same degree of influence on collaborative outcomes for all research teams and settings; nor are precise algorithms available for gauging the relative contributions of multiple contextual variables (e.g., those listed under each level of analysis shown in Figure 1) to collaborative success. For any given initiative, at least some of the important determinants of effective collaboration are likely to be specific to the type of transdisciplinary project or program undertaken (e.g., single versus multiple organizations and locations, large versus small numbers of participants and disciplinary perspectives).

At the same time, this review of the scientific literature on team performance identified certain intrapersonal and situational variables (e.g., empowering-leadership styles, the regularity and effectiveness of team communication, opportunities for informal face-to-face contact, members' readiness and preparation for transdisciplinary collaboration) that emerged across multiple research domains as important contributors to collaborative success within a broad array of transdisciplinary projects and programs (e.g., university-based research teams, community coalitions for health promotion, intersectoral partnerships for policy change). Moreover, these factors may act synergistically in some collaborative settings to influence team processes and outcomes in an interactive or cumulative fashion.[29,112]

What are the implications of these findings for designing and managing effective team science initiatives? Generally speaking, the evidence on team performance suggests the value of optimizing as many factors as possible that have been found to facilitate collaborative success (i.e., those listed in Tables 1 and 2) whenever a new team science initiative is developed and implemented. The research literature also suggests, however, that not all of the conditions listed under each analytic level of the proposed typology (Figure 1) must be present in all instances to ensure that a particular initiative is effective. Furthermore, efforts to optimize an unlimited array of contextual resources for all team science initiatives would be neither feasible nor justifiable in terms of cost-effectiveness criteria, especially considering the recent criticisms of team science and concerns about budgetary appropriations for transdisciplinary research programs versus single-investigator grants.[18,19] Thus, a more compelling strategy for developing and managing team science initiatives is to match the particular goals and structure of a transdisciplinary research program with targeted investments in those contextual resources (e.g., collaboration-readiness factors) that are specific to the project at hand and are most likely to be essential for its success.

Accordingly, it is useful to distinguish between the contextual determinants of collaborative success that are highly specific to the requirements of a given initiative and other, more broadly influential factors whose effects extend across a wider array of transdisciplinary research settings and programs. Before a team science initiative is launched, efforts should be made to ensure that, at a minimum, project-specific requirements for collaborative success are present at the outset (e.g., access to the requisite electronic infrastructure among team members who must coordinate their efforts across remote sites). To the extent that additional investments can be made to ensure that other generally influential conditions for success are present (e.g., leaders who have extensive experience in managing distance collaboration, frequent face-to-face meetings among team members over the course of a multisite collaboration), they should be undertaken to further improve the prospects for collaborative success.

When deciding how to allocate program-development funds (either to project-specific requirements alone or to a larger set of collaboration-readiness factors that include both project-specific and more generally influential determinants of success), it is important to consider the degree of complexity inherent in the proposed transdisciplinary science initiatives. Transdisciplinary science projects and programs can be arrayed along a continuum of complexity, ranging from simple to highly complex.

Key determinants of the complexity of transdisciplinary initiatives include: (1) the number of scientists participating in the initiative (e.g., a solo investigator working at the interface of two or more fields, a group of 2–3 scientists working at the same site, or 15–30 scientists collaborating across multiple organizations and geographic locations); (2) the diversity of disciplinary perspectives and scientific world views represented among participants, ranging from relatively similar to widely divergent; (3) the anticipated duration of the project or program (e.g., a 1–2 year project compared to a 5–10-year research and training initiative); (4) whether participants are working to accomplish a small or large number of programmatic goals (e.g., scientific discovery and integration, the effective training of new transdisciplinary scientists, translations of scientific findings into community health programs and policy initiatives, the improvement of population health outcomes); and (5) the organizational, analytic, and geographic scope of an initiative, reflected in the number of organizations, levels of analysis, and geographic sites incorporated within a particular program.

Earlier studies of transdisciplinary collaboration suggest that the more complex a transdisciplinary science initiative is, the larger the number of both project-specific and general collaboration-readiness factors required to ensure its success. For instance, many, if not most, of the contextual influences on collaborative effectiveness identified in earlier social psychological and organizational behavior studies (e.g., exemplary leadership styles, electronic communications infrastructure, training programs to prepare participants for the tensions inherent in transdisciplinary teamwork) should be less important to the success of individual scientists or very small teams of researchers working at the same site than the success of larger and more-diverse teams that are attempting to collaborate across multiple locations and establish translational partnerships with health practitioners and non-academic organizations in the local community. Similarly, to the degree that a transdisciplinary initiative has established a large number of diverse goals spanning scientific, training, policy, and public health outcomes, the contextual circumstances required to facilitate the attainment of those goals and the criteria for evaluating the team's effectiveness in meeting them become more varied and complex (*vis-à-vis* initiatives whose major collaborative goals are more narrowly targeted).

In sum, the preceding review of the research on team performance suggests that investments in team science initiatives should be allocated strategically prior to initiating new transdisciplinary research and training programs and be tailored to match the complexity of their goals and organizational structure. To accomplish this matching, it is important that project-specific audits be conducted to ascertain which of the contextual factors outlined in Table 2 and Figure 1 should receive the greatest priority and investment of resources prior to the launch of a new transdisciplinary program. Especially for more-complex transdisciplinary science and training initiatives that include large numbers of participants, encompass diverse goals, and span multiple organizations and sites, leaders should be chosen carefully to include individuals who have prior experience managing large-scale transdisciplinary programs and interpersonal styles that promote effective collaboration. Furthermore, new training programs for participants in large-scale team science initiatives should be developed to better prepare them for the challenges and complexities that often arise in transdisciplinary collaborations.[128] Finally, grant funding to support the establishment of long-term transdisciplinary research centers and programs should be targeted not only to prospective applicant teams that have demonstrated high levels of collaboration readiness prior to their initiation of the proposed project, but also to relatively less-experienced teams that show great scientific promise and whose collaborative success may be accelerated by targeted investments of funding aimed at increasing their readiness and resources for collaboration (e.g., the provision of shared research space, electronic infrastructure, or transdisciplinary training modules).

This paper was presented at the National Cancer Institute Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research, October 30–31, 2006, in Bethesda MD. The authors gratefully acknowledge support for this manuscript provided by an IPA contract to Daniel Stokols from the Office of the Director, Division of Cancer Control and Population Sciences of the National Cancer Institute; a predoctoral research award to Shalini Misra from NIH Roadmap Interdisciplinary Training Grant No. 15R13DK69500-03; and Cancer Research Training Award fellowships to Kara Hall and Brandie Taylor. The authors thank the four anonymous reviewers for their comments on an earlier version of the manuscript.

No financial disclosures were reported by the authors of this paper.

References

1. Kahn RL. An experiment in scientific organization. Chicago IL: The John D. and Catherine T. MacArthur Foundation, Program in Mental Health and Human Development. A MacArthur Foundation Occasional Paper, 1993. http://www.macfound.org/atf/cf/%7BB0386CE3-8B29-4162-8098-E466FB856794%7D/experiment_in_scientific_organization.pdf.
2. Nass SJ, Stillman B, eds. Large-scale biomedical science: exploring strategies for future research. Washington DC: The National Academies Press, 2003.
3. The National Academies. The National Academies Keck futures initiative. 2003. www.keckfutures.org.
4. NIH. NIH roadmap for medical research: interdisciplinary research. 2003. http://www.rwjf.org/applications/solicited/npo.jsp?FUND_ID=55113.
5. Robert Wood Johnson Foundation. RWJF active living research program. www.rwjf.org/applications/solicited/npo.jsp?FUND_ID=55113.
6. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.

7. Wuchty S, Jones BF, Uzzi B. The increasing dominance of teams in production of knowledge. Science 2007;316:1036–9. doi:10.1126/science.1136099.
8. NIH. BECON 2003 symposium on catalyzing team science (Day 1). 2003 June 23–24; Bethesda MD videocast.nih.gov/launch.asp?9924.
9. Pellmar TC, Eisenberg L, eds. Bridging disciplines in the brain, behavioral, and clinical sciences. Washington DC: IOM/The National Academies Press, 2000.
10. Klein JT. Crossing boundaries: knowledge, disciplinarities and interdisciplinarities. Charlottesville VA: University of Virginia Press, 1996.
11. Kessel FS, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
12. IOM. Enhancing the vitality of the National Institutes of Health: organizational change to meet new challenges. Washington DC: The National Academies Press, 2003.
13. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
14. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
15. Trochim WM, Marcus SE, Mâsse LC, Moser RP, Weld PC. The evaluation of large research initiatives: a participatory integrated mixed-methods approach. Am J Eval 2008;29:8–28.
16. Smith R. Measuring the social impact of research. BMJ 2001;323:528.
17. Morgan G, Kobus K, Gerlach KK, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003;5(1S):S11–S19.
18. Marks AR. Rescuing the NIH before it is too late. J Clin Invest 2006;116:844.
19. Weissmann G. Roadmaps, translational research, and childish curiosity. FASEB J 2005;19:1761–2.
20. Abrams DB, Leslie FM, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res 2003;5(1S):S5–S10.
21. Weingart P, Stehr N, eds. Practising interdisciplinarity. Toronto: University of Toronto Press, 2000.
22. Younglove-Webb J, Gray B, Abdalla CW, Purvis Thurow A. The dynamics of multidisciplinary research teams in academia. Rev Higher Educ 1999;22:425–40.
23. Rhoten D, Parker A. Education: risks and rewards of an interdisciplinary research path. Science 2004;306:2046.
24. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005 www.nap.edu/catalog.php?record_id=11153#toc.
25. Rhoten D. Final report: a multi-method analysis of the social and technical conditions for interdisciplinary collaboration. 2003. www.hybridvigor.net/publications.pl?s=interdis.
26. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
27. Fuqua J, Stokols D, Gress J, Phillips K, Harvey R. Transdisciplinary collaboration as a basis for enhancing the science and prevention of substance use and "abuse." Subst Use Misuse 2004;39:1457–514.
28. Klein JT. Interdisciplinarity: history, theory and practice. Detroit MI: Wayne State University Press, 1990.
29. Stokols D. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
30. Zerhouni EA. Translational and clinical science—time for a new vision. N Engl J Med 2005;353:1621–3.
31. Hays TC. The science of team science: commentary on measurements of scientific readiness. Am J Prev Med 2008;35(2S):S193–S195.
32. Guzzo RA, Dickson MW. Teams in organizations: recent research on performance and effectiveness. Annu Rev Psychol 1996;47:307–33.
33. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
34. Klein JT. Prospects for transdisciplinarity. Futures 2004;36:515–26.
35. Lawrence RJ. Housing and health: from interdisciplinary principles to transdisciplinary research and practice. Futures 2004;36:487–502.
36. Ramadier T. Transdisciplinarity and its challenges: the case of urban studies. Futures 2004;36:423–39.
37. Tyers M, Mann M. From genomics to proteomics. Nature 2003;422:193–7.
38. Gibbons MC. A historical overview of health disparities and the potential of eHealth solutions. J Med Internet Res 2005;7:e50.
39. td-net. Network for transdisciplinarity in sciences and humanities. 2005. www.transdisciplinarity.ch.
40. Minkler M, Wallerstein N, eds. Community-based participatory research for health. San Francisco: Jossey-Bass, 2003.
41. NIH. Centers for Population Health and Health Disparities: RFA ES-02-009. 2002. grants.nih.gov/grants/guide/rfa-files/RFA-ES-02-009.html.
42. Hare AP, Borgatta EF, Bales RF. Small groups: studies in social interaction. Rev. ed. New York: Knopf, 1965.
43. Cartright D, Zander A, eds. Group dynamics: research and theory. 3rd ed. New York: Harper & Row, 1968.
44. Bales RF. Interaction process analysis: a method for the study of small groups. Reading MA: Addison-Wesley Publishing Co., 1950.
45. Kerr NL, Tindale RS. Group performance and decision making. Annu Rev Psychol 2004;55:623–55.
46. Lipnack J, Stamps J. Virtual teams: reaching across space, time, and organizations with technology. New York: Wiley, 1997.
47. Festinger L, Schachter S, Back K. Social pressures in informal groups. Stanford CA: Stanford University Press, 1950.
48. Tuckman BW. Developmental sequence in small groups. Psychol Bull 1965;63:384–99.
49. Cohen SG, Bailey DE. What makes teams work: group effectiveness research from the shop floor to the executive suite. J Manag 1997;23:239–90.
50. Cooperrider DL, Peter F, Sorensen J, Yaeger TF, Whitney D, eds. Appreciative inquiry: an emerging direction for organization development. Champaign IL: Stipes Publishing LLC, 2001.
51. Ilgen DR, Hollenbeck JR, Johnson M, Jundt D. Teams in organizations: from input-process-outtput models to IMOI models. Annu Rev Psychol 2005;56:517–43.
52. Bennis W. The secrets of great groups. Leader to Leader 1997;3:29–33.
53. Reagans R, Zuckerman E, McEvily B. How to make the team: social networks vs. demography as criteria for designing effective teams. Adm Sci Q 2004;49:101–33.
54. Milliken FJ, Martins LL. Searching for common threads: understanding the multiple effects of diversity on organizational groups. Acad Manage Rev 1996;21:192–9.
55. Wiersema MF, Bantel KA. Top management team demography and corporate strategic change. Acad Manage J 1992;35:91–121.
56. Jackson SE, May KE, Whitney K. Understanding the dynamics of diversity in decision-making teams. In: Guzzo RA, Salas E, eds. Team effectiveness and decision making in organizations. San Francisco: Jossey-Bass, 1995:204–61.
57. Katz RL. The effects of group longevity on project communication and performance. Adm Sci Q 1982;27:81–104.
58. Harrison DA, Mohammed S, McGrath JE, Florey AT, Vanderstoep SW. Time matters in team performance: effects of member familiarity, entrainment, and task discontinuity on speed and quality. Personnel Psychol 2003;56:633–69.
59. Jackson JM, Harkins SG. Equity in effort: an explanation of the social loafing effect. J Pers Soc Psychol 1985;49:1199–206.
60. Janis I. Groupthink: psychological studies of policy decisions and fiascoes. 2nd ed. Boston MA: Houghton Mifflin, 1982.
61. Kayes AB, Kayes DC, Kolb DA. Experiential learning in teams. Simul Gaming 2005;36:330–54.
62. Latane B, Williams K, Harkins S. Many hands make light the work: the causes and consequences of social loafing. J Pers Soc Psychol 1979;37:822–32.
63. Okhuysen GA. Structuring change: familiarity and formal interventions in problem-solving groups. Acad Manage J 2001;44:794–808.
64. Weick KE. The social psychology of organizing. 2nd ed. Reading MA: Addison-Wesley Publishing Co., 1979.
65. Mullen B, Symons C, Hu L, Salas E. Group size, leadership behavior, and subordinate satisfaction. J Gen Psychol 1989;116:155–70.
66. Magjuka RJ, Baldwin TT. Team-based employee involvement programs: effects of design and administration. Personnel Psychol 1991;44:793–812. doi:10.1111/j.1744-6570.1991.tb00699.
67. Stewart GL. A meta-analytic review of relationships between team design features and team performance. J Manage 2006;32:29–54.
68. Vinokur-Kaplan D. Treatments that work (and those that don't): an application of Hackman's group effectiveness model to interdisciplinary teams in psychiatric hospitals. J Appl Behav Sci 1995;31:303–27.
69. Steele F. Making and managing high-quality workplaces: an organizational ecology. New York: Teachers College Press, 1986.

70. Sundstrom E, DeMeuse KP, Futrell D. Work teams: applications and effectiveness. Am Psychol 1990;45:120–33.
71. Brill M, Weidemann S. Disproving widespread myths about workspace design. Buffalo NY: BOSTI Associates, 2001.
72. Sonnenwald DH. Scientific collaboration: a synthesis of challenges and strategies. In: Cronin B, ed. Annual Review of Information Science and Technology, vol. 41. Medford NJ: Information Today, Inc., 2007.
73. Weber M. The theory of social and economic organization. New York: Oxford University Press, 1947.
74. Stogdill RM. Personal factors associated with leadership. J Psychol 1948;25:35–71.
75. House RJ, Baetz ML. Leadership: some empirical generalizations and new research directions. In: Cummings LL, Staw BM, eds. Leadership, participation, and group behavior. Greenwich CT: JAI Press, 1990:1–83.
76. Bales RF. Social interaction systems: theory and measurement. New Brunswick NJ: Transaction Publisher, 1999.
77. Fiedler FE. A theory of leadership effectiveness. New York: McGraw-Hill, 1967.
78. O'Connell MS, Doverspike D, Cober AB. Leadership and semiautonomous work team performance. Group Organ Manag 2001;27:50–65.
79. Cohen SG, Chang L, Ledford GE. A hierarchical construct of self management leadership and its relationship to quality of work life and perceived group effectiveness. Personnel Psychol 1997;50:275–308.
80. Collins J. Level 5 leadership: the triumph of humility and fierce resolve. Harv Bus Rev 2001;79:66–76.
81. Sivasubramaniam N, Murry WD, Avolio BJ, Jung DI. A longitudinal model of the effects of team leadership and group potency on group performance. Group Organ Manag 2002;27:66–96.
82. Bandura A. Self-efficacy: the exercise of control. New York: Freeman, 1997.
83. Ericksen J, Dyer L. Right from the start: exploring the effects of early team events on subsequent project team development and performance. Adm Sci Q 2004;49:438–71.
84. Strauss G. Workers' participation in management: an international perspective. In: Cummings LL, Staw BM, eds. Leadership, participation, and group behavior. Greenwich CT: JAI Press, 1990.
85. Cooperrider DL, Srivastava S. Appreciative inquiry in organizational life. In: Woodman RW, Pasmore WA, eds. Research in organizational change and development, vol. 1. Greenwich CT: JAI Press, 1987.
86. Lewin K. Resolving social conflicts. New York: Harper, 1948.
87. Monge PR, Cozzens MD, Contractor NS. Communication and the motivational predictors of the dynamics of organizational innovation. Organization Science 1992;3:250–74.
88. Edmondson AC. Psychological safety and learning behavior in work teams. Adm Sci Q 1999;44:350–83.
89. Ancona DG, Caldwell DF. Bridging the boundary: external activity and performance in organizational teams. Adm Sci Q 1992;37:634–65.
90. Olson GM, Olson JS. Distance matters. Human-Computer Interaction 2000;15(2/3):139–78.
91. Wageman R. Interdependence and group effectiveness. Adm Sci Q 1995;40:145–80.
92. Johnson DW, Johnson RT. Cooperation and competition: theory and research. Edina MN: Interaction Book Co., 1989.
93. Manz CC, Stewart GL. Attaining flexible stability by integrating total quality management and socio-technical systems theory. Organization Science 1997;8:59–70.
94. Finholt TA, Olson GM. From laboratories to collaboratories: a new organizational form for scientific collaboration. Psychol Sci 1997;8:28–36.
95. National Research Council. National collaboratories: applying information technology for scientific research. Washington DC: The National Academies Press, 1993.
96. Wulf WA. The collaboratory opportunity. Science 1993;261:854–5.
97. Mark G, Grudin J, Poltrock SE. Meeting at the desktop: an empirical study of virtually collocated teams. In: Proceedings of the Sixth European Conference on Computer Supported Work; 1999 Sept 12–16; Copenhagen, Denmark. Norwell MA: Kluwer Academic Publishers, 1999.
98. Finholt TA. Collaboratories as a new form of scientific organization. Econ Innov New Techn 2003;12:5–25.
99. Cairncross F. The death of distance: how the communications revolution will change our lives. Boston MA: Harvard Business School Press, 1997.
100. Jarvenpaa SL, Leidner DE. Communication and trust in global virtual teams. Organizational Science 1999;10:791–815.
101. Mayer RC, Davis JH, Schoorman FD. An integrative model of organizational trust. Acad Manage Rev 1995;20:709–34.
102. Rocco E. Trust breaks down in electronic contexts but can be repaired by some initial face-to-face contact. In: Proceedings of the Conference on Human Factors in Computing Systems—CHI '98; 1998 Apr 18–23; Los Angeles CA. New York: ACM Press/Addison-Wesley Publishing Co., 1998.
103. Sonnenwald DH. Managing cognitive and affective trust in the conceptual R&D organization. In: Houtari M, Iivonen M, eds. Trust in knowledge management and systems in organizations. Hershey PA: Idea Publishing, 2003.
104. Hollingshead AB, Contractor NS. New media and small group organizing In: Lievrouw LA, Livingstone S, eds. Handbook of new media: social shaping and consequences of ICTs. London/Thousand Oaks/New Delhi: Sage Publications, 2002.
105. Dourish P, Adler A, Bellotti V, Henderson A. Your place or mine? Learning from long-term use of audio-video communication. Comput Support Coop Work 1996;5:33–62.
106. Teasley S, Wolinsky S. Scientific collaboration at a distance. Science 2001;292:2254–5.
107. Israel BA, Schulz AJ, Parker EA, Becker AB. Review of community-based research: assessing partnership approaches to improve public health. Annu Rev Public Health 1998;19:173–202.
108. Lantz PM, Viruell-Fuentes E, Israel BA, Softley D, Guzman R. Can communities and academia work together on public health research? Evaluations results from a community-based participatory research partnership in Detroit. J Urban Health: Bull N Y Acad Med 2001;78:495–507.
109. Butterfoss FD, Goodman RM, Wandersman A. Community coalitions for prevention and health promotion. Health Educ Res 1993;8:315–30.
110. Cohen J. Balancing the collaboration equation. Science 2000;288:2155–9.
111. Fisher PA, Ball TJ. Tribal participatory research: mechanisms of a collaborative model. Am J Community Psychol 2003;32(3–4):207–16.
112. Altman DG. Sustaining interventions in community systems: on the relationship between researchers and communities. Health Psychol 1995;14:526–36.
113. Kumpfer KL, Turner C, Hopkins R, Librett J. Leadership and team effectiveness in community coalitions for the prevention of alcohol and other drug abuse. Health Educ Res 1993;8:359–74.
114. Stokols D. The future of interdisciplinarity in the School of Social Ecology. 1998. www.drugabuse.gov/ttuc/Readings.html.
115. Sonnenwald DH, Whitton MC, Maglaughlin KL. Evaluating a scientific collaboratory: results of a controlled experiment. ACM Trans Computer-Human Interaction 2003;10:150–76.
116. Jeffry P. Smoothing the waters: observations on the process of cross-disciplinary research collaboration. Soc Stud Sci 2003;33:539–62.
117. Creamer EG. Collaborators' attitudes about differences of opinion. J Higher Educ 2004;75:566–71.
118. Fuqua J. Transdisciplinary scientific collaboration: an exploration of the research process [dissertation]. Irvine (CA): School of Social Ecology, University of California, 2002.
119. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
120. Bruun H, Hukkinen J, Huutoniemi K, Klein JT, eds. Promoting interdisciplinary research: the case of the academy of Finland. Helsinki, Finland: The Academy of Finland, 2005.
121. Wray KB. The epistemic significance of collaborative research. Philos Sci 2002;69:150–68.
122. Havemann F. Collaboration behavior of Berlin life science researchers in the last two decades of the twentieth century as reflected in the Science Citation Index. Scientometrics 2001;52:435–43.
123. Cohen J, Linton M. Asia—the new frontier for HIV/AIDS. Science 2003;301:1650–5.
124. Ashton J, Grey P, Barnard K. Healthy cities: WHO's new public health initiative. Health Promot 1986;1:319–24.
125. Duhl L. An ecohistory of health: the role of "healthy cities." Am J Health Promot 1996;10:258–61.
126. WHO. The Jakarta Declaration on Leading Health Promotion into the 21st Century (Declaration from the 4th International Conference on Health Promotion). 1997 Jul 21–25; Jakarta, Indonesia. www.who.int/hpr/archive/docs/jakarta/english.html.
127. David PA, Spence M. Towards institutional infrastructures for e-science: the scope of the challenge. Oxford: University of Oxford, 2003.
128. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.

Evaluation of Interdisciplinary and Transdisciplinary Research

A Literature Review

Julie T. Klein, PhD

Abstract: Interdisciplinarity has become a widespread mantra for research, accompanied by a growing body of publications. Evaluation, however, remains one of the least-understood aspects. This review of interdisciplinary and transdisciplinary research evaluation categorizes lessons from the emergent international literature on the topic reviewed in 2007. It defines parallels between research performance and evaluation, presents seven generic principles for evaluation, and reflects in the conclusion on changing connotations of the underlying concepts of *discipline, peer,* and *measurement*. Interdisciplinary and transdisciplinary research performance and evaluation are both generative processes of harvesting, capitalizing, and leveraging multiple expertise. Individual standards must be calibrated, and tensions among different disciplinary, professional, and interdisciplinary approaches carefully managed in balancing acts that require negotiation and compromise. Readiness levels are strengthened by antecedent conditions that are flexible enough to allow multiple pathways of integration and collaboration. In both cases, as well, new epistemic communities must be constructed and new cultures of evidence produced. The multidisciplinary–interdisciplinary–transdisciplinary research environment spans a wide range of contexts. Yet seven generic principles provide a coherent framework for thinking about evaluation: (1) variability of goals; (2) variability of criteria and indicators; (3) leveraging of integration; (4) interaction of social and cognitive factors in collaboration; (5) management, leadership, and coaching; (6) iteration in a comprehensive and transparent system; and (7) effectiveness and impact.
(Am J Prev Med 2008;35(2S):S116–S123) © 2008 American Journal of Preventive Medicine

Introduction

Interdisciplinarity has become a widespread mantra for research, accompanied by a growing body of publications. Evaluation, however, remains one of the least-understood aspects. In the past, discussions of interdisciplinary and transdisciplinary evaluation did not constitute an identifiable literature. They were scattered across multiple forums, and they were longer on anecdotal, intuitive, and normative perspectives than on empirical, longitudinal, and large-scale studies. In the absence of clear guidelines, Laudel and Origgi[1] recount, faculty and administrators had to "muddle through." The three clusters of work in Figure 1,[1–28] though, form an emergent international literature identified in 2007 by cross-referencing publication citations, significant addresses, and discussions in electronic networks focused on the topic. Cluster 1 spans an international body of studies recognized in the April 2006 benchmark issue of *Research Evaluation* on interdisciplinary research assessment.[2] Cluster 2 centers on the concept of transdisciplinary team science in the U.S. highlighted in this supplement to the *American Journal of Preventive Medicine*.[14] Cluster 3 encompasses studies from the European transdisciplinary movement for trans-sector, problem-oriented research involving the participation of stakeholders in society.

The contexts of interdisciplinary and transdisciplinary research vary greatly, as well as the attendant methodologies and conceptual frameworks. Yet cross-cutting themes provide a comparative framework for thinking about evaluation that draws insights from qualitative and quantitative studies. This review defines parallels between research performance and evaluation, and then presents seven generic principles for evaluation. The conclusion addresses implications for the underlying concepts of *discipline, peer,* and *measurement*. Interdisciplinary and transdisciplinary research performance and evaluation are both generative processes of harvesting, capitalizing, and leveraging multiple kinds of expertise. Individual standards must be calibrated and tensions among different approaches carefully managed in balancing acts that require negotiation and compromise. Readiness levels are strength-

From the Interdisciplinary Studies Program/Department of English, Wayne State University, Detroit, Michigan

Address correspondence and reprint requests to: Julie T. Klein, PhD, 111 Linden Court, Ypsilanti MI 48197. E-mail: julietklein@comcast.net.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.010

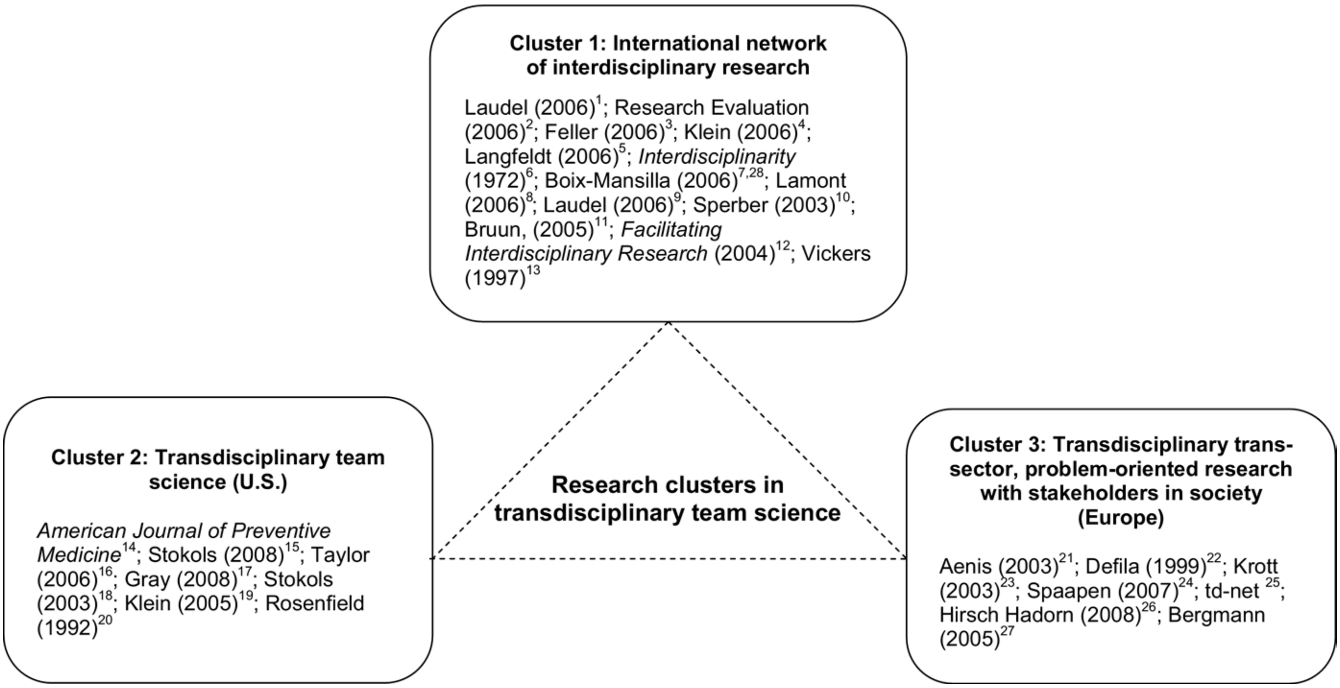


Figure 1. Clusters of emergent literature

ened by antecedent conditions that are flexible enough to allow multiple pathways of integration and collaboration. Appropriate epistemic communities must also be constructed and new cultures of evidence produced.

Research in the multidisciplinary–interdisciplinary–transdisciplinary environment is not a set of mutually exclusive categories. Research is too complex, Spaapen et al.[24] advise, to be put into boxes that ignore the particularities of context. In their introduction to this supplement, Stokols et al.[15] present recognized distinctions between multidisciplinary juxtapositions of disciplinary approaches and more robust interdisciplinary integrations and collaborations. In defining *transdisciplinary*, they adopt Rosenfield's connotation[20] of a process in which members of different fields work together over extended periods to develop novel conceptual and methodologic frameworks with the potential to produce transcendent theoretical approaches. This connotation is consistent with the earliest definition of *transdisciplinary*[6] as a common axiom that transcends separate disciplinary perspectives, exemplified by the overarching syntheses of general systems and ecology. A second major connotation in the European transdisciplinary movement should also be acknowledged: trans-sector, problem-oriented research involving a wider range of stakeholders in society. Both connotations are necessary for a full understanding of the spectrum of interdisciplinary and transdisciplinary research.

The evaluation of interdisciplinary and transdisciplinary research is a complex task. More than one discipline, profession, and field—or perhaps all three—are involved. Levels and subsystems differ, ranging from small projects to national research systems, from the personal and interpersonal to organizational and systemic scales, and from academic settings to trans-sector projects with external stakeholders. Criteria also vary across stages, from ex ante to ex post assessments, and programs and projects differ by knowledge domain, institutional location, goals, and type of integration. The scope of integration, in turn, varies from middle-range and narrow-gauged or horizontal forms of interdisciplinarity among neighboring disciplines with compatible epistemologies to broad-gauged, vertical, and grand-scale forms among disciplines with more divergent epistemologies.[16,18] In short, as Feller[3] emphasized in a 2006 symposium on interdisciplinary research evaluation at the American Association for the Advancement of Science (AAAS), the reality of interdisciplinary evaluation is shaped by multiples: multiple actors making multiple decisions in varied organizational settings with context-dependent measures of quality. As a result, Spaapen et al.[24] add, quality is a relative concept determined by relations within the environment of a group and their goals. Research must "attune a pluralism of interests and values" within a dynamic set of programs and contexts and with a variegated group of stakeholders.[24]

The heterogeneity of the multidisciplinary–interdisciplinary–transdisciplinary environment defies the quest for a single best procedure for research performance or evaluation. Yet the emergent literature,[1–5,7–28] suggests seven generic principles of evaluation (Table 1): (1) variability of goals; (2) variability of criteria and indicators; (3) leveraging of integration; (4) interaction of social and cognitive factors in collaboration; (5) manage-

Table 1. Correlation of principles and references

Principle number	Evaluation principles
1	Variability of goals[5,7,11]
2	Variability of criteria and indicators[7,12,28]
3	Leveraging of integration[7,14–16,18,19,22,23,28]
4	Interactions of social and cognitive factors in collaboration[16,18,21,22,24,27,28]
5	Management, leadership, and coaching[7,9,11,17,19,22,24]
6	Iteration in a comprehensive and transparent system[16,18,21,24]
7	Effectiveness and impact[12,22,23,28]

ment, leadership, and coaching; (6) iteration in a comprehensive and transparent system; and (7) effectiveness and impact. Klein[4] defined these principles earlier, but they are placed here within an expanded comparative framework that incorporates new work.

Principle #1. Variability of Goals

Interdisciplinary and transdisciplinary research are not driven by a single goal. Based on a comparative analysis of evaluation procedures in Europe and the U.S., Langfeldt[5] concluded that sensitivity to context and flexibility are fundamental. Two studies[7,11] in Cluster 1 underscore the principle of variability. When an Academy of Finland integrative research team examined how well the Academy was accommodating interdisciplinary research in all funding categories based on the analysis of research proposals and interviews,[11] the most important reason cited for selecting an interdisciplinary approach was typically an epistemological goal: the production of new and broad knowledge of a particular phenomenon. Informants also cited new approaches that are interesting and hold potential as well as synergies stimulated by sharing knowledge, skills, or resources. Others mentioned the development of technical equipment or products such as information technology protocols, medicines, and measuring devices. Broadly speaking, methodological interdisciplinarity dominated over more-challenging conceptual and theoretical forms, achieved typically by combining concrete methods or research strategies from different fields in order to test a hypothesis, answer a research question, or develop a theory.

A similar variety of goals appeared when a team from the Interdisciplinary Studies Project at Harvard University[7] interviewed researchers in five organizations with extensive experience in conducting interdisciplinary research. In a project involving physicists assessing their mathematical theories of innovation and network behavior, researchers favored qualities such as "the ability to predict" unstudied social and biological phenomena and "tangible success" in explaining something that had not been explained previously. In a project combining physiology, molecular biology, nanophysics, and materials science, scientists valued creation of an "unprecedented entity": for example, a vascularized artificial liver that "works" and has a "transforming effect" on organ transplantation surgical practice. Researchers engaged in pragmatic problem solving and product development placed a higher premium on viability, workability, and impact, while contributions seeking algorithmic models of complex phenomena were associated with simplicity, predictive power, and parsimony. Contributions seeking a more-grounded understanding of multidimensional phenomena, such as lactose intolerance or organ donation, favored work reaching new levels of comprehensiveness, careful description, and empirical grounding.[7] The key implication of this study is that variability of goals in turn drives variability of criteria and indicators of quality.

Principle #2. Variability of Criteria and Indicators

The Harvard team[7] identified two approaches to the assessment of interdisciplinary quality based on interview results. The first—conventional metrics—has been privileged traditionally. Informants reported being judged typically on indirect or field-based quality indicators: numbers of patents, publications, and citations; prestige rankings; and the approval of peers and a broader community. Hence, the first epistemic criterion in the study was consistency with multiple-"antecedent disciplinary knowledge." Credibility was strengthened by "fit" with disciplinary antecedents. Yet when work violated fundamental tenets or revealed limitations, additional justification was required.[7] Field-based measures, informants indicated, sidestep the question of what constitutes warranted interdisciplinary knowledge by relying on the social procedures of peer review, inter-subjective agreement, and consensus on what constitutes acceptable results. Informants were often critical of such "proxy" criteria, believing that they represent a strictly disciplinary assessment. More primary or epistemic measures of "good" work are needed that address the substance and constitution of the research, such as experimental rigor, aesthetic quality, fit between framework and data, and the power to address previously unsolved questions in a discipline.[28]

Other studies[12] affirm the principle of variability. The 2004 report *Facilitating Interdisciplinary Research*[12] from the U.S. National Academies of Science (NAS) cites outcomes in and feedback to multiple fields or disciplines; expanded expertise, vocabularies, and tool sets; the ability to work in more than one discipline; a greater proclivity toward interdisciplinary and transdisciplinary collaboration; and a widened sphere of professional reading. Individuals responding to national surveys preliminary to the report also cited participation in new subfields and departments as well as multidisciplinary advisory or review groups; new formal affiliations; and the co-mentoring of doctoral students. Changing career trajectories were gauged by new appointments, recognition within and outside a person's original field, and, in areas such as sustainability and health outcomes, new public-policy initiatives and altered protocols in health management.[12]

Principle #3. Leveraging of Integration

Studies of interdisciplinary and transdisciplinary research call attention not only to outcomes but also to the quality of the process. Integration is widely considered the crux of interdisciplinarity,[29] and Krott[23] deems integration the critical point for evaluation in transdisciplinary projects. Likewise, the Harvard Project[7] highlighted the epistemic criterion of balance in weaving perspectives into a coherent whole, and integration was one of four "hot spots" identified in the 2006 AAAS symposium, in the form of "reaching effective syntheses."[7] The heart of the process, Boix-Mansilla[28] explains, is leveraging integration. In linking processes of intellectual integration and collaboration, the introduction to this supplement[15] and studies[18] of the Transdisciplinary Tobacco Use Research Centers (TTURCs) also stress the role of antecedent conditions, including frequent opportunities for communication, structural support, and a transdisciplinary ethic.

Two sets of guidelines[19,22] stress the importance of engaging integration from the beginning. Klein's "Guiding Questions for Integration"[19] was created for ex ante evaluation of grant proposals in the TTURCs program and subsequently revised for Land & Water Australia's key document on integration in natural resource management. Klein highlights a number of evaluation questions aimed at fostering integration and monitoring relationships among organizational, methodologic, and epistemologic components of a project or program. Is the spectrum of disciplines and fields too narrow or too broad for the task at hand? Have relevant approaches, tools, and partners been identified? Is the structure flexible enough to allow for shifting groupings of individuals and context-related adaptations, deletions, and additions? Has synthesis unfolded through patterning and testing the relatedness of materials, ideas, and methods? Have known integrative techniques been utilized, such as the Delphi method, scenario building, general systems theory, and computer analyses of stakeholders' perspectives? And, is there a unifying principle, theory, or set of questions that provides coherence, unity, or both?

Defila and DiGiulio's[22] catalogue of criteria emerged from a study of trans-sector transdisciplinary research commissioned by the Swiss National Science Foundation. The catalogue provides a comprehensive set of building blocks to help construct either a self-evaluation or an external evaluation of a research program. The power of the generative approach to evaluation lies in its flexibility. All categories in the catalogue of criteria may not apply at all phases (e.g., scientific quality or integration/synthesis or project organization/management). The timing and number of evaluations can also be adjusted throughout stages, and the questions of who performs the evaluation and the weighting of criteria are left open, too.

Principle #4. Interaction of Social and Cognitive Factors in Collaboration

The studies of transdisciplinary collaboration in Clusters 2 and 3 (Figure 1) emphasize the interaction of social and cognitive factors. While recognizing familiar indicators such as publications, the logic model that emerged from studies of the TTURCs accords greater weight to collaboration and does not sharply separate cognitive–epistemic and social factors.[16,18] Comparably, Spaapen et al.[24] describe research in the multidisciplinary–interdisciplinary–transdisciplinary environment as a "social process of knowledge production." Studies of interdisciplinary collaboration concur (Amey and Brown,[30] Derry et al.[31]). In Cluster 1 (Figure 1), Boix-Mansilla[28] highlights the need to calibrate separate standards while managing tensions through compromise and negotiation. The ongoing and systematic communication of research partners and subprojects lessens the likelihood of shortfalls of integration. The clarification and negotiation of differences lessen misunderstanding and strengthen the conditions for consensual modes of work. Intellectual integration is leveraged socially through mutual learning and joint activities that foster common conceptions of a project or program and common assessments. Mutual knowledge emerges as novel insights are generated, disciplinary relationships redefined, and integrative frameworks built. Within a heterogeneous mix of disciplines, though, compromises must be made, and the best option may be a partial, negotiated consensus.

Drawing on experiences in trans-sector transdisciplinarity within European landscape studies, Aenis and Nagel[21] formulated two axiomatic considerations for evaluation: the meta-level of interdisciplinarity (communication among researchers) and participation (communication between researchers and regional actors). Communication and negotiation also lie at the heart of the *Evalunet Guide for Formative Evaluation of Research Projects*,[27] an initiative of the Institute for Social–Ecological Research in Germany. The question-based guide provides both basic and detailed criteria based on the empirical study of projects in European research institutes. Evaluation is defined a collaborative and discursive learning process. Individuals first address questions by themselves, and then arrive at a common plan together, rather than imposing a priori a universal scoring method. Like the Defila and DiGiulio catalogue,[22] the detailed criteria of the *Evalunet* guide are also flexible.

Principle #5. Management and Coaching

Competence, Klein[19] and Defila and DiGiulio[22] also concur, is defined partly in terms of how well the management of projects and programs implements consensus building and integration. Therefore, evaluation must consider how well the organizational structure fosters communication, including networking among subprojects. The organizational chart and task distribution must allow time for interaction, joint work activities, common instruments, and shared decision making. If a group is pushed too quickly toward integration, the crucial activities of building rapport and exploring ways to understand how each discipline approaches a research question are shortchanged, ultimately shortchanging the quality of the integration. Comparably, as participants[7] in the 2006 AAAS symposium exhorted, in the peer-review process expertise must be carefully managed if panelists are to calibrate their individual beliefs about the meaning of quality.

Leadership is another prominent theme. Gray[17] in this supplement categorizes three types of leadership tasks for transdisciplinary research. **Cognitive tasks** focus on meaning making through a mental model or mindset. Visioning and reframing stimulate ideas about how disciplines might overlap in constructive ways that generate new understandings and encourage collaborative work modes. **Structural tasks** entail management issues of coordination and information exchange, including focus and defining objectives, recruitment of expertise, and accountability for deadlines and deliverables. External boundaries must be spanned, and internal linkages and information flows brokered across different disciplinary cultures, status hierarchies, and organizational structures. **Process tasks** ensure constructive and productive interactions among team members, with the attendant subtasks of designing meetings, determining ground rules, identifying tasks that move partners toward their objectives, building trust, and ensuring effective communication (and, if necessary, removing a member). Ultimately, Gray[17] conceptualizes transdisciplinary collaboration as innovation networks, underscoring the need for network stability, knowledge mobility, and innovation appropriability.

Recently, the theme of coaching both the research and evaluation processes has emerged in Clusters 2 and 3 (Figure 1). Klein[19] and Defila and DiGiulio[22] recommend also using their evaluation guidelines to nurture integration during the actual course of research. Spaapen et al.[24] describe their Research Embedment and Performance Profile (REPP), which emerged from studies of agricultural and pharmaceutical research, as a coaching model rather than a jury model. The REPP facilitates the graphic depiction of the main activities of a group (e.g., publications, collaboration, innovation) and its performance, fostering self-reflection about process, performance, and mission.[24] For peer review, the Academy of Finland integrative research team[11] recommends that national funding agencies coach the interdisciplinary and transdisciplinary process, and Laudel[9] cites an exemplary model. The German *Sonderforschungsbereiche* (SFBs) are networks of research groups that receive funding for collaborative research programs. The core of the review process is a series of group discussions among the reviewers and between reviewers and applicants. A group or center is also evaluated every third year by largely the same reviewers. Repeating the process ensures that reviewers gain the necessary competence and a communication base over time, facilitated by the empowerment of applicants and the enforced interdisciplinary learning of reviewers.[9]

Principle #6. Iteration and Transparency in a Comprehensive System

Studies of interdisciplinary and transdisciplinary collaboration highlight the overriding importance of iteration to ensure collaborative input, transparency, and common stakeholding. In the TTURCs logic model,[16,18] indicators are not restricted to a single phrase. They have a feedback relationship that a strictly linear model of evaluation cannot capture. The logic model moves from the basic activities of centers (training, collaboration, and integration) and the earliest expected outcomes. Basic activities lead to new and improved methods, science, and models that are tested and lead to publications. Publications, in turn, foster recognition and the institutionalization of transdisciplinary research that feed back on the overall infrastructure and capacity of centers, resulting in increased support for basic activities. They also provide a content base for communicating results to a broader community. Recognition, in turn, provides a secondary impetus for communications and publications. Policy implications result as well from communications and publications, while translation to practice is influenced by improved interventions. Health outcomes, for example, are influenced both by treatments and health practices related to policy changes.[16,18]

Two models in Cluster 3 furnish insights from fields of application. Aenis and Nagel[21] used logical-framework (log-frame) analysis to define impact indicators in agricultural research, based on the systematic elaboration of objectives at the beginning. The central insight is that the mobility of participants and interaction and communication patterns furnish a heuristic for identifying differences in social domains or contexts for knowledge production. In each context, differing expectations exist, with attendant norms, values, and priorities.[21] The REPP method of Spaapen et al.[24] facilitates the reconstruction of both the relevant environment and the performance of a group within it, seeking patterns and profiles rather than imposing a priori measurements. A quantifiable benchmark, though, can be set for each indicator in consultation with researchers and policymakers. Scores are plotted on a radar-like graph that represents variegated activities. If a group claims to contribute to the development of sustainable greenhouse production, for example, the profile should show that empirically. The key dynamics are feedback to the mission of a program and transparency of criteria. Feedback allows for context-related adaptations that improve the research process and conceptual framework. Transparency requires that both evaluators and participants are informed of criteria from the outset and, ideally, are involved in defining them.[24]

Principle #7: Effectiveness and Impact

Principle #7 returns full circle to Principles #1 and #2: variability of goals drives variability of criteria and indicators. The third criteria of quality in the Harvard study was effectiveness in advancing epistemological understanding or pragmatic viability in concrete settings. Unintended consequences and unforeseeable long-term impacts, though, cannot be captured by a priori measures, and they may have multiple consequences. "Interdisciplinary impacts," Boix-Mansilla cautions, "are often diffused, delayed in time, and dispersed across diverse areas of study and patterns of citation practice."[28] Defila and DiGiulio agree, admonishing that many long-term effects cannot be predicted or checked in five-year periods, let alone annual measures.[22] In trans-sector transdisciplinary, Krott notes, different target groups also make use of knowledge in ways unknown at the start of a project.[23] Likewise, studies[16,18] of the TTURCs stipulate that the appropriate time frame for assessing returns on investment or the value-added contributions of large-scale transdisciplinary collaboration may require broad historical perspectives spanning two or more decades.

The NAS report *Facilitating Interdisciplinary Research*[12] cites numerous examples of long-term impacts that could not be predicted or measured fully at the outset. Research on nitrate and sulphate cycles, for instance, proved relevant not only for agricultural production but also for research on global climate change and the greenhouse effect. Developing the engineering technologies necessary to achieve space flight led to advances in computer control of engineering processes that subsequently fostered improvements in the reliability of industrial products and processes. Large programs also stimulate new understanding in multiple fields, a long-term effect evident in the Human Genome Project, the Manhattan Project, and in broad efforts such as the theory of plate tectonics and the development of the fiber-optic cable. Moreover, generative technologies such as magnetic resonance imaging are enhancing research capabilities in an expanding number of areas through new instrumentation and informational analysis.[12]

Conclusion: The Logic of *Discipline*, *Peer*, and *Measurement*

An emergent literature is a benchmark of both what is known and what remains to be known. Key insights from this literature appear in Table 2. Yet findings are still dispersed across multiple forums, even with systematic efforts to disseminate information by groups such as the Europe-based td-net.[25,26] Longitudinal empirical studies of interdisciplinary and transdisciplinary evaluation remain few in number and need testing in local contexts. Access to in vivo deliberations is still limited in peer review, and governments lack clearly defined and tested criteria for prioritizing funding across the spectrum of disciplinary and multidisciplinary–interdisciplinary–transdisciplinary research. And, more broadly, unquestioned assumptions about three underlying concepts—*discipline*, *peer*, and *measurement*—continue to cloud the discourse on evaluation.

Disciplines provide crucial knowledge, methodologies, and tools for interdisciplinary and transdisciplinary work. However, in many discussions, disciplines are still treated uncritically as monolithic constructs. Studies of disciplinarity reveal that disciplines exhibit a striking heterogeneity, and that boundary crossing has become a marked feature of contemporary research. Some disciplines, Vickers[13] observes, have undergone so much change that characterizing them as stable matrices with consensual evidentiary protocols is problematic. Some new interdisciplinary and transdisciplinary fields also reject disciplinarity in whole or in part, and, Sperber[10] observed in an online virtual seminar, the purpose of interdisciplinary work may aim to undermine current understanding in disciplines. A standard assessment procedure can help in charting a program's interactions within a broader environment and ensuring that work is sound and reliable.[24] Yet stringent evaluation criteria for both research and evaluation may be counterproductive, especially, Langfeldt[5] warns, for risk taking and "radical interdisciplinarity." Conflicting assumptions about quality meet head-on during *peer* review, whether in ex ante evaluations of grant proposals and priority setting in national research systems or in ex post assessments of research performance and outcomes. A "commonly agreed yardstick" must be developed to "moderate the conservative forces" of traditional research communities, safeguarding against bias.[5]

Identifying experts who fit the "problem space" is crucial, because they form an appropriate interdisciplinary epistemic community. The task is more difficult, though, in emerging fields where the criteria of excellence are not defined yet and the pool of qualified

Table 2. Key insights

Principle number	Evaluation principles	Key insights
1	Variability of goals	**Variances:** size, scope, scale, level and subsystem, degree of integration in multidisciplinary–interdisciplinary–transdisciplinary environment **Multiple goals:** for example, epistemologic or methodologic forms, product development, pragmatic problem solving *Range of stages*: ex ante, intermediate, ex post
2	Variability of criteria and indicators	**Two major approaches to quality assessment:** conventional metrics; indirect, field-based, and proxy criteria vs primary or epistemic measures of warranted interdisciplinary knowledge in the substance of the work **Expanded indicators:** for example, experimental rigor, aesthetic quality, new explanatory power, feedback to multiple fields, enhanced research capabilities, changing career trajectories, new public policies and treatment protocols, long-term impacts and unforeseen consequences
3	Leveraging of integration	**Key factors:** balance in weaving perspectives together into new whole, reaching effective synthesis, antecedent conditions for readiness **Criteria for leveraging and evaluating integration:** organizational, methodologic, and epistemologic components; strategies that promote communication and consensus; generative boundary objects
4	Interactions of social and cognitive factors in collaboration	**Requirements:** for example, calibrating separate standards, managing tensions among conflicting approaches, clarifying and negotiating differences among all stakeholders, compromising, communicating in ongoing and systematic fashion, engaging in mutual learning and joint activities
5	Management, leadership, and coaching	**Requirements:** managing tensions in balancing acts, consensus building, integration, interaction, common boundary objects, shared decision making, coaching the process **Categories of leadership tasks:** cognitive, structural, and processual
6	Iteration and feedback in a comprehensive and transparent system	**Requirements:** attuning a pluralism of values and interests, iterative work to insure collaborative inputs, transparency to include common stakeholding, feedback to the mission in a dynamic framework, mobility of participants, interaction and communication patterns
7	Effectiveness and impact	**Expanded indicators:** sensitivity to variety of goals in Principle 1 and variety of criteria and indicators in Principle 2; inclusion of unpredictable long-term impacts, returns on investment, value-added

experts is often smaller. In highly innovative work, developing validation criteria to gauge progress often becomes part of the actual process of inquiry.[7] The summary report[2] of the 2006 AAAS symposium cites a number of strategies in funding agencies, including creating "on-the-fly" electronic review teams, using "interpreters" who bridge the epistemic gap among content experts, asking candidates for grants to contribute the names of suitable peers, and forming joint panels and "matrix" schemes that combine disciplinary reviews with full-panel reviews among discipline-based and interdisciplinary members. Special funding programs may bypass conventional control mechanisms, but they run the risk of marginalizing interdisciplinary and transdisciplinary research.[2]

Lamont and colleagues' study[8] of fellowship competitions in social sciences and humanities furnishes a powerful analytical lens for thinking about interdisciplinary and transdisciplinary evaluation. Building on the work of Max Weber and Emile Durkheim, the team described the production of legitimacy that occurs in review panels. Review panels are "sites where new rules of fairness are redefined, reinvented and slowly recognized."[8] In the absence of customary rules, consensus on what constitutes a good proposal must be negotiated. Equilibria must be achieved between the familiarity and distance of non-expertise, between transparency and opacity, expertise and subjectivity, and between interdisciplinary appeal and disciplinary mastery. Methodologic pluralism is key to arriving at a judgment that is both consistent and limits bias.[8]

Finally, the logic of *measurement* returns the question of evaluation full circle to the gap between conventional metrics and the complexity of interdisciplinary and transdisciplinary research. Paralleling interdisciplinary studies and learning assessment, interdisciplinary and transdisciplinary research process and evaluation are grounded in the philosophy of constructivism. Appropriate evaluation is made, not given. It evolves through a dialogue of conventional and expanded indicators of quality. Traditional methodology and statistics have a role to play, but they are not sufficient. In the past, Sperber[10] admonishes, people seeking the legitimization of interdisciplinary initiatives had to be both parties and judges, educating their evaluators in the process of doing and presenting their work. The emergent literature provides both parties and judges with an authoritative portfolio of methodologies, instruments, design models, guidelines, and conceptual frameworks anchored by a growing body of case studies and findings. They neither impose nor forestall evaluation awaiting a single-best or universal method that would be antithetical to the multidimensionality and context-specific nature of interdisciplinary and transdisciplinary work. They facilitate informed definition of the task and credible tracking of the actions and outcomes attendant to the substance, constitution, and value of the research.

The author thanks Daniel Stokols, Brandie Taylor, Kara Hall, Richard Moser, and Veronica Boix-Mansilla for feedback on earlier drafts. The author also thanks Shalini Misra (doctoral candidate in the School of Social Ecology, University of California Irvine) for preparation of the figures. Research evaluation will also be the focus of a chapter by Katri Huutoniemi in the forthcoming *Oxford Handbook of Interdisciplinarity*, edited by Robert Frodeman, Julie Thompson Klein, and Carl Mitcham (2009).

No financial disclosures were reported by the author of this paper.

References

1. Laudel G, Origgi G. Introduction to a special issue on the assessment of interdisciplinary research. Research Evaluation 2006;15:2–4.
2. Special issue on the assessment of interdisciplinary research. Research Evaluation 2006;15:1–80.
3. Feller I. Multiple actors, multiple settings, multiple criteria: issues in assessing interdisciplinary research. Research Evaluation 2006;15:5–15.
4. Klein JT. Afterword: the emergent literature on interdisciplinary and transdisciplinary research evaluation. Research Evaluation 2006;15: 75–80.
5. Langfeldt L. The policy challenges of peer review: managing bias, conflict of interests and interdisciplinary assessments. Research Evaluation 2006; 15:31–41.
6. Interdisciplinarity: problems of teaching and research in universities. Paris: Organization for Economic Cooperation and Development, 1972.
7. Boix-Mansilla V, Feller I, Gardner H. Quality assessment in interdisciplinary research and education. Research Evaluation 2006;15:69–74.
8. Lamont M, Mallard G, Guetzkow J. Beyond blind faith: overcoming the obstacles to interdisciplinary evaluation. Research Evaluation 2006;15: 43–55.
9. Laudel G. Conclave in the Tower of Babel: how peers review interdisciplinary research proposals. Research Evaluation 2006;15:57–68.
10. Sperber D. Why rethink interdisciplinarity? In: Interdisciplines: rethinking interdisciplinarity. 2003. www.interdisciplines.org/interdisciplinarity/papers/1.
11. Bruun H, Hukkinen J, Huutoniemi K, Klein JT. Promoting interdisciplinary research: the case of the Academy of Finland. Academy of Finland Publication Series 8/05. Helsinki: Academy of Finland, 2005.
12. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2004. www.nap.edu/catalog.php?record_id=11153#toc.
13. Vickers J. [U]nframed in open, unmapped fields: teaching and the practice of interdisciplinarity. Arachné: An Interdisciplinary Journal of the Humanities 1997;4:11–42.
14. Stokols D, Hall KL, Taylor BK, Moser RP, Syme LS, eds. The science of team science: assessing the value of transdisciplinary research. Am J Prev Med 2008;35(2S):S77–S252.
15. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
16. Taylor BK, Moser RP, Trochim WM, et al. The evaluation of large initiatives (ELI) project at the National Cancer Institute: key findings and lessons learned. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD.
17. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
18. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
19. Klein JT. Guiding questions for integration. Proceedings of the Integration Symposium 2004. Canberra: Land & Water Australia; 2005. CD-ROM #EC040735. land&waterAustralia lwa.gov.au.
20. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
21. Aenis T, Nagel UJ. Impact indicator definition within a transdisciplinary research group. In: Tress B, Tress G, van dern Valk AJJ, Fry G, eds. Interdisciplinary and transdisciplinary landscape studies: potential and limitations. Delta Series 2. Wageningen, Netherlands: WUR Alterra, 2003.
22. Defila R, DiGiulio A. Evaluating transdisciplinary research. Panorama: Swiss National Science Foundation Newsletter 1999;1:4–27. www.ikaoe.unibe.ch/forschung/ip/Specialissue.Pano.1.99.pdf.
23. Krott M. Evaluation of transdisciplinary research. In: Encyclopedia of life support systems. Oxford: EOLSS Publishers, 2003. www.eolss.net.
24. Spaapen J, Dijstelbloem H, Wamlink F. Evaluating research in context: a method for assessment. 2nd ed. The Hague, Netherlands: Consultative Committee of Sector Councils for Research and Development, 2007.
25. td-net. Network for transdisciplinarity in sciences and humanities. www.transdisciplinarity.ch/.
26. Hirsch Hadorn G, Hoffmann-Riem H, Biber-Klemm S, et al. Handbook of transdisciplinary research. The Netherlands: Springer, 2008.
27. Bergmann M, Brohmann B, Hoffmann E, et al. Quality criteria for transdisciplinary research: a guideline for the formative evaluation of research projects. Frankfurt am Main: Institute for Social-Ecological Research (ISOE), 2005. ISOE-Studientexte, No. 13/English Version. downloads.isoe.de/literatur/evalunet_e.htm.
28. Boix-Mansilla V. Assessing expert interdisciplinary work at the frontier: an empirical exploration. Research Evaluation 2006;15:17–29.
29. Klein JT, Newell WH. Advancing interdisciplinary studies. In: Gaff J, Ratcliffe J, eds. Handbook of the undergraduate curriculum: a comprehensive guide to purposes, structures, practices, and change. San Francisco: Jossey-Bass, 1996.
30. Amey MJ, Brown DF. Breaking out of the box: interdisciplinary collaboration and faculty work. Greenwich CT: Information Age Publishing, 2004.
31. Derry SJ, Schunn CD, Gernsbacher MA, eds. Interdisciplinary collaboration: an emerging cognitive science. Mahwah NJ: Lawrence Erlbaum Associates, Inc., 2005.

Enhancing Transdisciplinary Research Through Collaborative Leadership

Barbara Gray, PhD

Abstract: Transcending the well-established and familiar boundaries of disciplinary silos poses challenges for even the most interpersonally competent scientists. This paper explores the challenges inherent in leading transdisciplinary projects, detailing the critical roles that leaders play in shepherding transdisciplinary scientific endeavors. Three types of leadership tasks are considered: cognitive, structural, and processual. Distinctions are made between leading small, co-located projects and large, dispersed ones. Finally, social-network analysis is proposed as a useful tool for conducting research on leadership, and, in particular, on the role of brokers, on complex transdisciplinary teams.
(Am J Prev Med 2008;35(2S):S124–S132)

Introduction

Interest in transdisciplinary research has burgeoned in the last 10 years. Transdisciplinary research refers to scientific inquiry that cuts "across disciplines, integrating and synthesizing content, theory and methodology from any discipline area which will shed light on the research questions."[1] Impetus for this new trend stems from the increasing complexity of scientific problems,[2,3] from the exploration of basic research issues, from the need to solve societal problems (like sustainability and debilitating diseases), and from stimuli from generative technologies such as the Internet and magnetic resonance imaging[2,3] as well as from the increasingly wide distribution of knowledge in educated societies.[4]

Transdisciplinarity, as distinguished from multidisciplinarity and interdisciplinarity,[5] requires that researchers invent new science together by exploring research questions at the intersection of their respective fields, conducting joint research projects and "developing methodologies that can be used to re-integrate knowledge."[6] While the distinctions between interdisciplinarity and transdisciplinarity may be difficult to tease out in practice, McMichael's notion[7] that transdisciplinarity promotes "theoretical, conceptual, and methodological reorientation with respect to core concepts of the participating disciplines" is, perhaps, the most helpful. Rather than as an alternative, transdisciplinarity is envisioned as a complement to ongoing discipline-based scientific inquiry that "might lead to a different, higher, plane of inquiry"[7] and enable different questions to be asked.

According to the International Center for Transdisciplinary Research,

> It [transdisciplinarity] occasions the emergence of new data and new interactions from out of the encounter between disciplines. It offers us a new vision of nature and reality. Transdisciplinarity does not strive for mastery of several disciplines but aims to open all disciplines to that which they share and to that which lies beyond them."[8]

Transcending the well-established and familiar boundaries of disciplinary silos, however, poses challenges for even the most interpersonally competent scientists.

This paper offers four contributions to the study of transdisciplinarity. First, it briefly explores the challenges inherent in working transdisciplinarily. Second, it focuses on the critical role of leadership in the shepherding of transdisciplinary scientific endeavors. Third, it examines the differences between single and distributed leadership in transdisciplinary teams. Finally, it conceptualizes transdisciplinary collaborations as innovation networks and illustrates how social-network analysis can augment the research on leadership in transdisciplinary teams.

The Challenges of Transdisciplinary Scientific Endeavors

The challenges of working across disciplines have been chronicled in a number of arenas. Numerous studies[9–14] have identified the difficulties associated with achieving this kind of integrated vision among scientists,[9,10] within business,[11] and in cross-sectoral and global collaborative teams.[12–14] While some scientific endeavors are likely to suffer from the "groupthink"

From the Smeal College of Business Administration, Pennsylvania State University, University Park, Pennsylvania

Address correspondence and reprint requests to: Barbara Gray, PhD, Center for Research in Conflict and Negotiation, Smeal College of Business Administration, Pennsylvania State University, 404 Business, University Park PA 16802. E-mail: bgray@psu.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.03.037

which many have suggested explained the team failure that led to the Challenger disaster,[15,16] transdisciplinary teams are more likely to experience the opposite problem. *Groupthink* refers to the suppression of differences within a team and its inability to bridge power differences. In transdisciplinary projects, misunderstanding and disagreement are much more likely. Squabbles among scientists about the validity of each other's conceptual frameworks, mismatches between rewards stressing disciplinary competence over innovation, and institutional disincentives have impeded or prevented successful transdisciplinary endeavors.[9,17,18]

For transdisciplinary teams, success may also be elusive if researchers lack a common problem focus.[19] For example, a team of agricultural economists, philosophers, and hydrologists, trying to solve agricultural problems, faced conflicts over finding a suitable framework and methodology for the study that would be considered cutting-edge by their individual disciplines.[9] In other transdisciplinary teams, the needs of stakeholders outside of academia, rather than just the needs with scientific potential, must be integrated with—or even drive—scientific activity, but this does not match the scientists' preferred approach to the topic.[20]

Finally, the absence of process skills (e.g., decision making, problem solving, conflict resolution, information exchange, coordination, and boundary management) has also been noted as a crucial detriment to collaboration.[21–24] In transdisciplinary relationships, this absence includes resolving questions of legitimacy, ameliorating power differences, and integrating diverse aims.[16,22,25,26] For example, university engineers[26] helping to solve irrigation projects in Ecuador favored their own expertise over local knowledge from the community that ultimately proved essential to the project's success.[26] In light of all these challenges to the building of transdisciplinary teams, leaders with the skills to manage collaboratively may make the difference between success and failure in transdisciplinary efforts.

Leadership Tasks for Enhancing Transdisciplinary Collaboration

What roles can leaders play to overcome or minimize these classic failures in decision making, planning, and cognition while, at the same time, spurring innovation and creative problem solving in transdisciplinary teams? In general, research has demonstrated that appropriate leadership can enhance the overall effectiveness of teams and increase the satisfaction of team members.[27–29] To build a model of leadership appropriate for transdisciplinary collaborations, findings from empirical research on diverse teams and in multiparty settings are utilized, because in those contexts team members must also transcend differences to ensure performance success.[21,29–32] Thus, leadership models for transdisciplinary teams are not necessarily unique, but share many process concerns with other teams (such as cross-cultural teams[33]or those trying to resolve complex societal conflicts[21,24,32] in which the management of differences is critical for tapping the team's full potential.

One model of leadership for multiparty collaborative endeavors proposes that leadership provides "the mechanisms that lead a collaboration's policy and activity agenda in one direction rather than another."[32] From this perspective, leadership can be conceptualized as creating a mental model, or mindset, to which followers adhere. Thus, the role of leadership involves sense making and, consequently, is cognitive in nature. Another approach stresses leadership qualities and identifies the structural roles that leaders must enact to ensure success. For example, Young[19] reports the need for a leader who is modest, benevolent, visionary, and strong, and identifies a list of leadership tasks that parallel those of project management, including providing focus and defining objectives; recruiting the necessary expertise; and ensuring the project's accountability (e.g., for deadlines, deliverables). A third approach emphasizes the need for process leadership, such as facilitating conflicts among members.[22,33] These tasks can be grouped into three general categories: cognitive, structural, and processual. Each of them will be discussed in detail.

Cognitive tasks. Viewing the leadership of transdisciplinary initiatives as a cognitive task means that leadership involves the management of meaning.[34,35] Leaders manage meaning for others by introducing a mental map of desired goals and the methods for achieving them while at the same time promoting individual creativity. Transformational leaders high on charisma, for example, are seen as powerful shapers of their followers' aspirations,[36] which positively affects team performance.[37] In transdisciplinary collaborations, this means a leader motivates followers by aligning the followers' self-concepts and individual scientific aspirations with the larger transdisciplinary mission.[37,38]

In transdisciplinary research, the cognitive tasks of leadership largely consist of visioning and framing. Here the visioning is an appreciative task that appeals less to the followers' complicity with achieving a pre-established goal and more to the unleashing of their own curiosity and creativity. This visioning process is referred to as *intellectual stimulation* by transformational leadership researchers,[36] and includes leader behaviors that promote divergent thinking, risk taking, and challenges to established methods.[36,37,39] Transdisciplinary leaders need to be able to envision how various disciplines may overlap in constructive ways that could generate scientific breakthroughs and new understanding in a specific problem area. They themselves need to appreciate the value of such endeavors, be able to communicate their vision to potential collaborators, and construct a climate that fosters this collaboration. Limmerick and Cunnington[31] describe this as "getting the mind-set right," which to them means both understanding and believing that working in an alliance is preferable to other modes of organization.

Beyond that, visioning should help transdisciplinary participants to break out of past mindsets and open up the content of new agendas.[33,36] Leaders engaged in visioning engage in the leadership task described as *framing*—the construction of a mental model that provides a sense-making device for team members, captures their beliefs and abilities, and motivates them to work productively together.[30] Most importantly for transdisciplinary projects, such visioning encourages members to reframe their extant conceptual frameworks. Such reframing requires the suspension of current assumptions and the introduction of a vision that turns participants' current mindsets upside down, jars them loose from their conceptual moorings, and creates an opening in which the previously unthinkable can become reality.[40,41] These frame shifts can result from the introduction of a new metaphor,[42] from the adoption of a new gestalt (e.g., a figure/ground shift), from moving up or down a level of abstraction in thinking,[41] or from deciphering meaning that transcends two cultures.[33] In this sense, then, transdisciplinary leaders attempt to create breakthrough visions for their colleagues.

The visioning role of transdisciplinary leaders is needed on two levels. First, on a content level to conceptualize and inspire the frame shifts described above. Visioning techniques can be employed to help people conceptualize the kinds of outcomes that might be possible through their collaboration. Techniques such as search conferences[43,44] and appreciative inquiry[45–47] may prove useful for this in the initial phase of transdisciplinary collaboration. *Search conferences* refer to efforts to build a common understanding of the domain or problem under consideration by imaging the desired futures that the researchers could pursue. *Appreciative inquiry* encourages the review of the positive aspects of the participants' working relationship to date as a launching pad for introducing change.[45–47] Applying search techniques to transdisciplinary teams would involve asking team members to identify the assumptive frameworks underlying their disciplinary views and the current and anticipated trends likely to influence their discipline's research in the future. For cancer research, for example, they might list behavioral changes that are likely to influence the incidence of cancer in the short-, medium-, and long-term future, and then construct predictions about their likelihood and potential effects.

The consideration of these various scenarios from the perspective of many different disciplines triggers reframing by the juxtaposition of unknown outcomes, unlikely outcomes, or both with expected ones.[43,44] If using an appreciative-inquiry approach, team members might extract the generative aspects of their most creative or productive projects from the past and build these into their current work. Interestingly, these kinds of visioning techniques can also promote relationship building among collaborators: ". . . a short, intense, whole system meeting enables something not available in any other way: A gestalt of the whole in all participants that dramatically improves their relationship to their work and their coworkers."[44]

A second level of visioning that transdisciplinary leaders need to encourage relates to the process of working collaboratively. Working constructively with diverse others in any context requires patience, tolerance, openness, listening, and conflict-resolution capability. While again these skills are not unique to transdisciplinary teams, they are clearly beneficial. Transdisciplinary team members queried about their leaders quickly identified these attributes in them, using phrases like: *She listens*, *he sees the possibilities*, *she builds bridges*, and they model this kind of behavior for their teams.[48] The process responsibilities associated with transdisciplinary leadership are considered in more detail below.

Frame change, by necessity, must also contend with the problem of language. "The language problem arises because the same words are used in quite different ways in different disciplines."[49] By recognizing this potential problem, transdisciplinary leaders can foster the development of a common language that is meaningful for team members along with the development of respect for each contributor's models and methods.[50,51] Some transdisciplinary projects report constructing a glossary of key terms without which members from each discipline make idiosyncratic interpretations of terms that result in confusion and misunderstandings.[48]

Another cognitive task required of transdisciplinary team leaders is judgment. Leaders must be able to make discriminating decisions about numerous issues. For example, judgments are required about the scope of the project, as this description[51] of the judgment calls involved in the Transdisciplinary Tobacco Use Research Centers initiative within the National Cancer Institute illustrates: Leaders had to manage a balance between depth and breadth as each center's theme evolved, in order to optimize the potential of scientific inquiry while remaining realistic about the strengths, gaps, and logistics of undertaking such a research endeavor.[51] Other judgment calls concern determining whom to invite onto the project, which new projects are the most promising, and how to deploy resources once participants are on board.

Structural tasks. Structural-leadership tasks address the team's need for coordination and information exchange—both within the team and between the team and external actors. The structure of the social network linking transdisciplinary the participants and leaders' positions within the team can enhance the team's overall performance through the creation of social capital or the ability to take advantage of network connections.[39,52,53] Previous research found that leaders who occupy positions of centrality in networks were highly educated, low in neuroticism, low in adversarial centrality, and had values similar to those of their teammates.[54] Research on brokers (who occupy key positions between others) in transdisciplinary networks reveals they are high on the Big Five Personality factor of openness, displayed an ability to imagine and propose potential collaborations among researchers, and engaged in active transdisciplinary mentoring of junior faculty.[48] Such leaders reported that they not only engaged in but enjoyed these matchmaking roles and were acknowledged for them by their colleagues. Most had had positive transdisciplinary mentoring themselves, and, in addition, were also seen as people who got things done.[48]

Research shows that both transformational leaders and their direct reports occupy central positions in their organizations' advice and influence networks[52] which enables them to garner greater social capital.[52,53] Managing both of these boundaries successfully involves boundary spanning[55,56] and brokering,[57–59] both of which are essential to the effective work of the team. Boundary-spanning activities are critical for teams engaged in innovation because they enable the teams to secure and convey information from and to groups outside their boundaries.[55] Among the boundary-spanning tasks identified as key for transdisciplinary teams are gaining and maintaining sound institutional commitment and support,[17] acquiring funds to manage emerging areas of research and training, devoting adequate attention to and securing funds for infrastructure, and building bridges to other centers and new disciplines.[48,51]

One form of boundary spanning essential for transdisciplinary team construction is brokerage. As noted above, in social-network terms, brokers link groups of actors who are not otherwise connected to each other. Brokers occupy "structural holes" at the crossroads between groups of actors.[59] Thus, brokers intervene by building linkages and increasing information flow among previously unrelated parties.[57,59] Because of their unique vantage point, brokers have access to a wider array of information than others within a network and, because they have one foot in each of several camps, can decipher differences among the camps and translate among them.[60] Brokers often serve as conflict-handlers to iron out disputes and misunderstandings among groups.[58] Brokers can also ameliorate power and status differences among diverse groups.[61] Given that transdisciplinary teams comprise junior and senior researchers, postdoctorate fellows, graduate students, and research assistants, the potential for status issues to mar communications seems inevitable.

The primary function of brokers in these situations is to ensure standing for low-power partners and to provide a conduit for information transfer and negotiations among partners of differential power. These tasks are not always easy, however, given that ego enhancement goes hand in hand with academic pursuits. Brokers with cultural fluency can serve as translators to facilitate alliances across cultural boundaries.[62] Cultural fluency refers to "recognizing identities and inviting divergent ways of making meaning into our awareness."[62] This kind of experience (i.e., the ability to tap into the experiences of or see through the lenses of other disciplines) is precisely what enables creative problem solving and reframing in public-policy arenas.[41,63]

One structural innovation within universities that has fostered interdisciplinary work is the creation of intercollege research institutes administered outside the traditional departmental structure.[18] These bring visibility to particular research activities that might not otherwise be recognized as important (e.g., materials, environment, transportation).

> There is unquestionable evidence that scholars and their students from diverse disciplines can work together effectively on common complex problems with tangible benefits to all, if careful thought is given as to how to encourage and sustain such interaction over a period of time.[18]

Launching and sustaining transdisciplinary research efforts requires leadership in the form of strong advocates at the top of universities, and university administrators need to be evaluated on the breadth of vision and encouragement for transdisciplinary research that they exhibit.[18]

Processual tasks. Attending to the process dynamics of a transdisciplinary team demands an especially important set of interpersonal skills that are critical to successful team collaboration.[20–22,58,62] Process leadership includes a host of activities related to ensuring that the interactions among team members are constructive and productive. Several subtasks fall under the umbrella task of attending to the processual aspects of the team: designing meetings (e.g., deciding when plenary or small-group meetings, caucuses, or joint data collection may be most productive); determining what ground rules might be useful; identifying tasks to move the partners toward their objectives; building trust among the partners; ensuring that effective communication is occurring; garnering buy-in from team members and their institutions; and mediating conflicts that are likely to arise[58] as team members strive to understand and integrate concepts, frameworks, and methodologies that may threaten their disciplinary comfort zones. Some of these resemble more traditional project-management tasks (such as goal setting, planning, coordinating information exchange, and monitoring progress), but others require more interpersonally oriented skills. Leadership intervention in the affective aspects of team life can prove especially beneficial, because interpersonal tensions generate negative emotions that erode the open exchange of ideas.[63] The vicissitudes of evaluation and re-application for funding can also affect the emotions of team members.[63] At these times, effective leaders need to display good listening skills, empathy, and the ability to reorient the team's efforts toward their long-term goals.

To summarize: Critical to promoting effective collaboration are leaders who "have the credibility to get the right people together to create visions, solve problems, and reach agreements about implementable actions."[31] It is important to note, however, that these leadership tasks need not necessarily be performed by a single leader. Instead, they could be handled in a distributed fashion by multiple members within a transdisciplinary team.[64] This issue is addressed in the next section.

One Leader Or Many?

Stokols et al.[63] have detailed the differences in complexity and geographic dispersion associated with transdisciplinary collaborations. While some projects may involve a small group of researchers who are collocated at a single institution, others may involve virtual, cross-institutional relationships with many scientists at each institution. Each of these extremes poses different challenges for transdisciplinary leadership, suggesting that a contingency perspective on transdisciplinary leadership may be useful.

Table 1 offers a contingency framework highlighting the different leadership tasks and skills required in different transdisciplinary circumstances. For example, in a small co-located project, a single, centralized leader may be sufficient to provide the charisma and coordination functions to promote effective collaboration within a transdisciplinary team.[38] In these settings, centralized leaders can maintain close connection to others in the team and enjoy informal, face-to-face connections that foster information exchange, coordination, and emotional support.[39,52,53] Process interventions that instill creativity and teambuilding are not only feasible but likely to improve transdisciplinary outcomes in these settings. Still, as noted earlier, without institutional champions higher up in the organization, even these small collaborations could experience limited success.[18,61]

Table 1. Types of collaboration and corresponding leadership characteristics

Type of transdisciplinary collaboration	Characteristic features of leadership
Small and collocated	Single leader Central leader Informal connections Face-to-face processes Teambuilding Leader needs process skills
Large and dispersed	Multiple leaders/champions Leaders in brokerage positions Coordination needed among leaders Leaders as translators and conflict-handlers

For larger, more dispersed teams with multiple sites, multiple leaders and champions who collaborate on key tasks may be essential. Multiple leaders can ensure that each separate unit builds commitment and buy-in to the transdisciplinary mission.[65] However, they also need to design effective coordination and information-exchange among these geographically disperse units. In these settings, it is useful to view them as innovation networks.[66] In such networks, multiple leaders link loosely connected actors but "lack the authority to issue commands" and participants "are not obliged to comply."[66] Three critical areas for leaders in innovation networks are managing network stability, knowledge mobility, and innovation appropriability.[66] Managing network stability ensures that the network remains intact even if some members come and go. Leaders who manage knowledge mobility ensure that necessary information is transferred among network partners. Managing innovation appropriability refers to garnering benefits from network activities. For transdisciplinary collaborations, this would translate into gaining appropriate recognition through publications.

For dispersed innovation, network leaders need to perform brokerage roles in order to link diverse units for whom informal, face-to-face connections are not possible. Brokers offer cross-cutting ties that enable them to acquire "vision advantage"[59]:

> . . . opinion and behavior are more homogenous within than between groups, so people connected across groups are more familiar with alternative ways of thinking and behaving, which is an advantage in detecting and developing rewarding opportunities. Specifically, there is a vision advantage . . .. New options emerge from selection and synthesis across structural holes.[59] Thus, because brokers can span structural holes, they can understand a problem from multiple perspectives and facilitate widening of frames by members of each unit (or discipline).[64]

Additionally, multiple leaders can increase the sustainability of transdisciplinary collaborations when research results need to be disseminated to community participants.[65] These leaders function as champions to ensure that community concerns are understood and incorporated into plans for implementation.[21,65] Multiple leaders may also be crucial on teams in which members have similar levels of expertise, albeit in many different disciplines. In such cases, process leadership

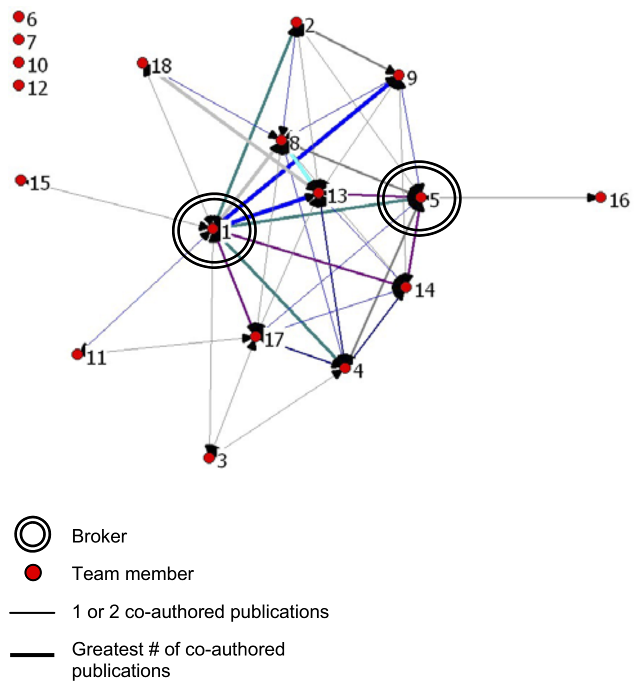


Figure 1. Example of brokers in a social network

may be of particular importance to ensure that everyone's expertise is acknowledged and respected and that no single discipline dominates the proceedings.

Studying Transdisciplinary Collaborations As Innovation Networks

If transdisciplinary collaborations are conceived of as innovation networks, then social-network analysis may prove to be a useful tool for studying these collaborative initiatives and, in particular for studying leadership roles within these networks.[67] Social-network analysis maps the relations within a group as a pattern of ties among the actors. Network analysis focuses on the entire system of linkages rather than on specific dyad connections.

One previous study[68] of interdisciplinary research used this technique to study the extent of interaction among researchers and to assess which personnel were critical for fostering collaboration. Figure 1 depicts a social network map diagram (a sociogram) of a transdisciplinary group at one institution. The nodes represent individual team members. The data are drawn from the researchers' co-authored publications during a single year. The thicker the lines connecting actors, the more they publish jointly. Individuals 8 and 13 have the greatest number of joint publications; Individuals 1 and 9 and Individuals 1 and 13 have the next-highest level of co-authored work. Team Members 6, 7, 10, and 12 have no co-authored publications with other team members for the year in question. These members may be newcomers to the team (e.g., recently recruited graduate students) or ongoing members whose expertise is not yet aligned with that of others on the team. A network study of one research center promoting interdisciplinarity found that researchers did link up across disciplines (84% of the researchers' connections formed after the center was created), but that graduate and postdoctoral students had more interdisciplinary contacts than faculty did.[68]

Social-network techniques use a measure called *betweenness centrality* to identify brokers within teams.[57,59] Betweenness centrality reflects the degree to which an actor links to individuals who are not otherwise linked to anyone else. In Figure 1, it can be seen that Persons 1 and 5 are clearly brokers among the team, because they connect Teammates 15 and 16 (and, to a lesser extent, Teammate 11) to the rest of the team. Thus, brokers facilitate information exchange[59] by connecting these outliners and their diverse views to the team. Additionally, to the extent that team members have diverse contacts outside the team, they too may leverage those brokerage roles to import novel insights into the team. According to Burt, "Research has strategic value when an observer sees how a finding has implications for what other people see as unrelated theory. A creative spark on which serendipity depends is to see bridges where others see holes."[59] Figure 2 depicts five different types of brokerage roles.[57] For large, dispersed transdisciplinary teams, brokers who function as representatives and liaisons are the most

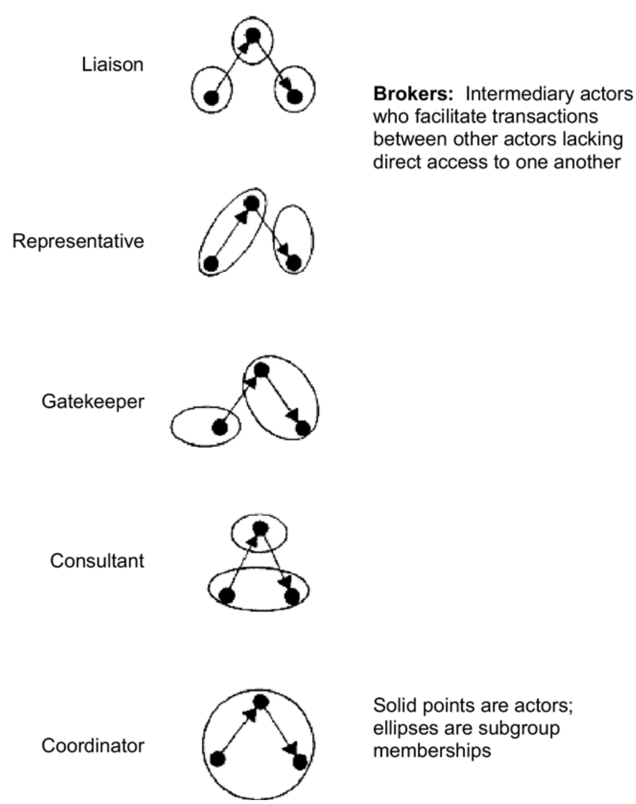


Figure 2. Types of brokers[57]

crucial because they are the only links connecting diverse groups (such as researchers from different disciplines).

Three advantages accrue to people in brokerage positions. They can access a wider array of information, get it earlier, and can control information diffusion.[59] Because of their unique position, brokers not only can leverage their vision advantage to identify and create new opportunities, but they are also viewed as attractive candidates to include in these opportunities.[59] And, because they receive specialized information from the diverse groups they connect, they can serve as translators—a particularly important role for transdisciplinary collaborations in which scientific assumptions and jargon can impede researchers. Recent research[48] on brokers' functions in a software development team that consisted of two geographically disparate and historically separate groups found that brokers played important roles as mediators of conflict. While other team members saw conflicting schemas within the team (arising from a clash of localized, parochial experiences), brokers did not.[48] While brokers noted the potential downsides of such conflicts for the team, they viewed them instead as opportunities to bridge differences within the team and stepped up as self-appointed conflict-handlers among their colleagues. Consequently, rather than using their vision advantage for their own entrepreneurial gains (as Burt[59] argues), these brokers performed critical process tasks for the project by serving as mediators of the conflicts rooted in historical, parochial differences.[57] Additionally, brokers were the only team members viewed as experts by both groups[57] (which is also true of centralized leaders in smaller teams[65]). Obstfeld[69] found brokers playing similar roles in the innovation teams that he studied.

Conclusion

Transdisciplinary teams provide a fascinating new venue for the study of collaboration and collaborative leadership in particular. To be successful in these venues, leaders must assume a pivotal role in surmounting the obstacles inherent in transdisciplinary collaborations and in facilitating the emergence of major discoveries from these endeavors.[69,70] Three general tasks of transdisciplinary leaders were outlined in this paper: cognitive, structural, and processual. Effective cognitive leadership provides a vision that links and motivates transdisciplinary researchers to step beyond their disciplinary lens, relax old assumptions, and search for creative frame-breaking solutions. Effective structural leadership adds value by creating needed bridges among unconnected parties. Effective processual leadership encourages trust and turns potentially destructive conflict into constructive interactions.

With increasing size and geographic dispersion, the task of transdisciplinary leadership becomes more complex, making the need for multiple leaders with different skills and network relationships a distinct possibility. While informal, centralized leadership may be sufficient for small, co-located teams, multiple leaders who serve as brokers to connect more disparate and unconnected groups of researchers are needed for larger projects. Shared decision making principles, close coordination, mutual respect, and highly refined process skills are vital for these leaders to sustain effective transdisciplinary collaborations.

To date, transdisciplinary leadership is mentioned briefly in descriptive studies of such projects[6,10,50] The model of transdisciplinary leadership presented here has drawn on that descriptive research, but also has incorporated empirical research on collaboration and network studies from other arenas. Both social-network analyses and close observational examination of leaders' behavior[71] in transdisciplinary efforts is needed to strengthen understanding of the distinctive requirements for leaders in these contexts. Social-network studies of how transdisciplinary networks evolve over time could provide promising insights into the structural patterns that contribute to innovative transdisciplinary outcomes. Examination of whether transformation leadership behaviors are suitable for bridging disciplinary boundaries would also be useful as would obtaining leaders' and followers' perceptions of how they transcended critical differences in paradigms, assumptions, theories, and methods. Understanding what motivates researchers to engage in transdisciplinary research would also be useful, because motivations can be both internal and external. Federal funders can promote such efforts through specific grant structures; academic institutions can create conducive or prohibitive cultures for transdisciplinary research; and individual researchers may have personal propensities and training that motivates them to pursue such projects. Most likely, however, it is the combination of personal motivation, institutional support, and external funding that will enable transdisciplinary efforts to thrive.[50] Still, individual researchers need to weight the costs and benefits of transdisciplinary work for themselves. Without facilitative leadership, potential participants may judge the likelihood of such payoffs to be slim.

In essence, success in transdisciplinary endeavors is not solely the responsibility of leaders. Nonetheless, the achievement of major innovations hinges on whether leaders have the capacity to enable deep diversity to thrive while simultaneously forging integration across disciplinary boundaries within their teams.

No financial disclosures were reported by the author of this paper.

References

1. Russell W. Forging new paths—transdisciplinarity in universities. 2000. www.wisenet-australia.org/issue53/transdis.htm.
2. Colwell R, Eisenstein R. From microscope to kaleidoscope: merging fields of vision. In: Klein JT, Grossenbacher-Mansuy W, Haberli R, Bill A, Scholz RW, Welti M eds. Transdisciplinarity: joint problem solving among science, technology and society—an effective way for managing complexity. Basel: Birkhauser Verlag, 2001.
3. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005. www.nap.edu/catalog.php?record_id=11153#toc.
4. Gibbons M, Limoges C, Nowotny H, Schwarzman S, Scott P, Trow M. The new production of knowledge: the dynamics of science and research in contemporary societies. Stockholm: SAGE Publications Ltd., 1994.
5. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
6. Sommerville MA, Rapport DJ, eds.Transdisciplinarity: recreating integrated knowledge. Montreal QC, Canada: McGill-Queens University Press, 2002.
7. McMichael AJ. What makes transdisciplinarity succeed or fail? First Report. In: Somerville MA, Rapport DJ, eds. Transdisciplinarity: recreating integrated knowledge. Oxford, UK: EOLSS Publishers Ltd., 2000.
8. The International Center for Transdisciplinary Research (CIRET). Charter of transdisciplinarity. Adopted at the First World Congress of Trandisciplinarity. 1994 Nov 2–6; Convento da Arrábida, Portugal. nicol.club.fr/ciret/english/charten.htm.
9. Younglove-Webb J, Gray B, Abdalla C, Purvis Thurow A. The dynamics of multidisciplinary research teams in academia. Rev Higher Educ 1999;22:425–40.
10. Klein JT, Grossenbacher-Mansuy W, Haberli R, Bill A, Scholz RW, Welti M, eds. Transdisciplinarity: joint problem solving among science, technology and society—an effective way for managing complexity. Basel: Birkhauser Verlag, 2001.
11. Eaton J. Management communication: the threat of groupthink. Corporate Commun Int J 2001;6:183–92.
12. Gray B. Obstacles to success in educational collaborations. In: Wang M, Rigby L, eds. School/community connections: exploring issues for research and practice. San Francisco: Jossey-Bass, 1995.
13. Cramton C. The mutual knowledge problem and its consequences for dispersed collaboration. Organization Sci 2001;12:346–71.
14. Vansina L, Taillieu T, Schruijer S. "Managing" multiparty issues: learning from experience. In: Woodman RW, Pasmore WA, eds. Research in organizational change and development. Vol. 11. Greenwich CT: JAI Press, 1998.
15. Hirokawa R, Gouran D, Martz A. Understanding the sources of faulty group decision making: a lesson from the Challenger disaster. Small Group Behavior 1988;19:411–33.
16. Moorhead G, Ference R, Neck CP. Group decision fiascoes continue: Space Shuttle Challenger and a revised groupthink framework. Hum Relat 1991;44:539–50.
17. Klein JT. Crossing boundaries: knowledge, disciplinarities and interdisciplinarities. Charlottesville: University Press of Virginia, 1996.
18. Remick FJ. Barriers to organized interdisciplinary research in a university environment. In: Roy R, ed. The interdisciplinary imperative: interactive research and education, still an elusive goal in academia. Lincoln NE: The Writers' Club Press [imprint of iUnivers.com, Inc.], 2000.
19. Young K. What makes transdisciplinarity succeed or fail? Second report. In: Somerville MA, Rapport DJ. eds. Transdisciplinarity: recreating integrated knowledge. Oxford, UK: EOLSS Publishers Ltd, 2000.
20. Hollaender K, Leroy P. Reflections on the interactive sessions. In: Klein JT, Grossenbacher-Mansuy W, Haberli R, Bill A, Scholz RW, Welti M., eds. Transdisciplinarity: joint problem solving among science, technology and society—an effective way for managing complexity. Basel: Birkhauser Verlag, 2001.
21. Gray B. Collaborating: finding common ground for multiparty problems. San Francisco: Jossey-Bass, 1989.
22. Wondolleck J. The importance of process in resolving environmental disputes. Environ Impact Assess Rev 1985;5:341–56.
23. Schwartz R. The skilled facilitator. San Francisco: Jossey-Bass, 2002.
24. Gray B, Schruijer S. Integrating multiple voices: working with collusion in multiparty collaboration. In: Steyaert C, Van Looy B, eds. Relational processes, London: Sage Publications, forthcoming.
25. Huxham C, Vangen S. Managing to collaborate. Oxford, UK: Routledge, 2005.
26. Bouwen R, Craps M, Santos D. Multi-party collaboration: building generative knowledge and developing relationships among "unequal" partners in local community projects in Ecuador. Concepts and Transformation 1999;4:133–51.
27. Maier N. Assets and liabilities in group problem solving. Psychol Rev 1967;74:239–49.
28. Fleishman EA, Harris EF. Patterns of leadership behavior related to employee grievances and turnover. Personnel Psychol 1962;15:43–56.
29. Fairhurst GT, Sarr RA. The art of framing: managing the language of leadership. San Francisco: Jossey-Bass, 1996.
30. Limmerick D, Cunnington B. Managing the new organization: a blueprint for networks and strategic alliances. San Francisco: Jossey-Bass, 1993.
31. Chrislip DE, Larson CE. Collaborative leadership: how citizens and civic leaders can make a difference. San Francisco: Jossey-Bass, 1994.
32. Huxham C, Vangen S. 2000. Leadership in the shaping and implementation of collaboration agendas: how things happen in a (not quite) joined up world. Acad Manage J 2000;43:1159–75.
33. Von Glinow MA, Shapiro DL, Brett JM. Can we talk, and should we? Managing emotional conflict in multicultural teams. Acad Manag Rev 2004;29:578–92.
34. Pfeffer J. Management as symbolic action: the creation and maintenance of organization paradigms. In: Cummings LL, Staw B, eds. Research in Organizational Behavior. Vol 3. Greenwich CT: JAI Press, 1981.
35. Smircich L. Organizations as shared meaning. In: Pondy LR, Frost P, Morgan G, Dandridge T, eds. Organizational symbolism. Greenwich CT.: JAI Press, 1983.
36. Bass B. Leadership and performance beyond expectations. New York: Free Press, 1985.
37. Kirkpatrick SA, Locke EA. Direct and indirect effects of three core charistmatic leadership components on performance and attitudes. J Appl Psychol 1996;81:36–51.
38. Shamir B, House R, Arthur M. The motivational effects of charismatic leadership: a self-concept-based theory. Organization Sci 1993;4:577–94.
39. Bonno JE, Anderson MH. The advice and influence networks of transformational leaders. J Appl Psychol 2005;90:1306–14.
40. Moore CM, Long G, Palmer P. Visioning. In: Susskind L, MacKearnan S, Thomas-Larmer J, eds. The consensus building handbook. Thousand Oaks CA: Sage Publications, 1999.
41. Schon DA, Rein M. Frame reflection: toward the resolution of intractable policy conflicts. New York: Basic Books, 1994.
42. Lakoff G, Johnson M. Metaphors we live by. Chicago: University of Chicago Press, 1980.
43. Emery M, Purser R. The search conference: a powerful method for planning organizational change and community action. San Francisco: Jossey-Bass, 1996.
44. Weisbord M, Janoff S. Faster, shorter, cheaper may be simple; it's never easy. J Appl Behav Sci 2005;41:70–83.
45. Cooperider DL, Srivastva S. Appreciative inquiry in organizational life. In: Pasmore WA, Woodman RW, eds. Research in organization development and change. Vol. 1. Greenwich CT: JAI, 1987.
46. Barrett FJ, Fry RE. Appreciative inquiry: a positive approach to building cooperative capacity. Taos NM: Taos Institute Publishing, 2005.
47. Cooperider DL, Whitney D. Appreciative inquiry: a positive revolution in change. New York: Berret-Koehler, 2005.
48. Gray B, Ren H, Susman G. Brokers' roles as boundary spanners in knowledge-intensive teams. Working paper, Center for Research in Conflict and Negotiation and Center for the Management of Technological and Organizational Change, Smeal College of Business Administration, Pennsylvania State University, October 30. 2007.
49. Nicolescu B. Voss K-C, trans. Manifesto of transdisciplinarity. SUNY Series in Western Esoteric Traditions. Albany NY: SUNY Press, 2002.
50. Salter L, Hearn A. Outside the lines: issues in interdisciplinary research. Montreal QC, Canada: McGill-Queen's University Press, 1996.
51. Morgan GD, Kobus K, Gerlach KK, Neighbors C, Lerman C, Abrams DB, Rimer BK. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003;5(1S):S11–S19.
52. Brass DJ. Social capital and organizational leadership. In: Zaccaro SJ, Klimoski RJ, eds. The nature of organizational leadership: understanding the performance imperatives confronting today's leaders. San Francisco: Jossey-Bass, 2001.
53. Lowe KB, Kroeck KG, Sivasubramaniam N. Effectiveness correlates of transformation and transactional leadership: a meta-analytic review of the MLQ literature. Leadership Quarterly 1996;7:385–425.
54. Klein KJ, Beng-Chong L, Saltz JL, Mayer DM. How do they get there: an examination of the antecedents of centrality in team networks. Acad Manage J

2004:47:952–63. www-management.wharton.upenn.edu/klein/documents/Klein_Lim_Saltz_Mayer_2004.pdf.
55. Ancona DG, Caldwell DF. Bridging the boundary: external activity and performance in organizational teams. Administrative Science Quarterly 1992;37:634–65.
56. Tushman M. Special boundary roles in the innovation process. Administrative Science Quarterly 1977;22:587–603.
57. Fernandez RM, Gould RV. A dilemma of state power: brokerage and influence in the National Health Policy. AJS 1994;99:1455–91.
58. Gray B, Susman G, Ren H. Brokers' roles in knowledge management teams: expertise, information and schema conflicts. Proceedings of the Academy of Management Meeting; 2005 Aug 5–10; Honolulu HI.
59. Burt RS. Brokerage and closure: an introduction to social capital. New York: Oxford University Press, 2005.
60. Westley F, Vrendenberg H. Strategic bridging: the alliances of business and environmentalists. J Appl Behav Sci 1991;27:65–90.
61. Gray B. 2008. Intervening to improve interorganizational partnerships. In: Huxham C, Cropper S, Ebers M, Ring P. Handbook of interorganizational relations. Thousand Oaks CA: Sage Publications, forthcoming.
62. LaBaron M. Bridging cultural conflict. San Francisco: Jossey-Bass, 2003.
63. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
64. Bolman LG, Deal TE. Reframing organizations. San Francisco: Jossey-Bass, 1991.
65. Altman DG. Sustaining interventions in community systems: on the relationship between researchers and communities. Health Psychol 1995;4:526–36.
66. Dhanaraj C, Parke A. Orchestrating innovation networks. Acad Manage Rev 2006;31:659–69.
67. Scott J. Social-network analysis: a handbook. London: Sage Publications, 1991.
68. Rhoten D. Final report, National Science Foundation BCS-0129573: a multimethod analysis of the social and technical conditions for interdisciplinary collaboration. 2003. www.hybridvigor.net/interdis/pubs/hv_pub_interdis-2003.09.29.pdf.
69. Obstfeld D. Social networks, the tertius iunguns orientation and involvement in innovation. Administrative Science Quarterly 2005;50:100–30.
70. Hollingsworth R, Hollingsworth EJ. Major discoveries and biomedical research organizations: perspectives on interdisciplinarity, nurturing leadership, and integrated structure and cultures. In: Weingart P, Stehr N. Practicing interdisciplinarity. Toronto: University of Toronto Press, 2000.
71. Sanson-Fisher RW, Poole AD, Harker J. Behavioral analysis of ward rounds within a general hospital psychiatric unit. Behav Res Ther 1979;17:333–48.

Transdisciplinary Training

Key Components and Prerequisites for Success

Justin M. Nash, PhD

Abstract: The training of transdisciplinary science is distinct in its intention to develop scientists who synthesize the theoretical and methodologic approaches of different disciplines. As a result, transdisciplinary scientists are better prepared to address the complexities of health problems. The most common form of transdisciplinary training is the multi-mentor apprenticeship model, with each mentor training from his or her own discipline. The transdisciplinary trainee is faced with many challenges, including learning the languages and cultures of different disciplines along with learning how to navigate within and between disciplines. The trainee also confronts unique career development risks. The climb up the academic ladder can be slower, rougher, and less linear than that of the trainee's single-disciplinary-trained peers. A number of factors can help the trainee in overcoming the challenges: being able to develop a core set of values and behaviors that are essential for transdisciplinary scientists; having the commitment and support of training institutions, training directors, and mentors; and having training structures and processes in place to prevent the training and trainee from naturally regressing back to familiar single-disciplinary approaches. There is relatively little known empirically about transdisciplinary training. Future efforts can focus on developing a better understanding of the unique characteristics of transdisciplinary training, identifying the effective elements that relate to training outcomes, defining the critical outcome metrics at different time points during and following training, and creating toolkits to help with training processes.
(Am J Prev Med 2008;35(2S):S133–S140)

Introduction

The complexity of health problems, combined with rapid technologic advances to address them, has intensified the call for researchers to more explicitly break from isolated disciplines and use integrative, transdisciplinary, scientific approaches.[1] Transdisciplinary science can be conducted by collaborative teams with members from different scientific disciplines and even nonscientific professions (e.g., architecture, city planning, law). Alternatively, transdisciplinary science can be conducted by individual scientists who become integrative in their disciplinary approach to research.[2,3] Kessel et al.[4] present case studies of collaborative teams of scientists and individual scientists who are integrative in their work. Examples of case studies from their volume will be used to illustrate key points. For example, Jay Kaplan, a physical anthropologist at Wake Forest University, and Stephen Manuck, a psychologist at the University of Pittsburgh, use a team approach. Each relies on his own discipline-specific expertise to collaborate in their examination of the role of behavior in the development of heart disease.[5] On the other hand, Richard J. Davidson is an individual scientist who is integrative in his examination of the neural substrates of emotion.[6]

Transdisciplinary training can occur at any level of career development. At an early career stage, doctoral training can be inherently transdisciplinary. The PhD program in Social Ecology at the University of California Irvine is an example of a doctoral program that has an established record of training scientists who are transdisciplinary. Early career transdisciplinary training is advantageous in that students are more readily acceptable of different disciplinary approaches and learn to conceptualize across theoretical perspectives and multiple levels at the outset of their scientific experience. Early career transdisciplinary training has the limitation, however, of not providing what some, including Kaplan,[5] would consider important. Students do not receive grounding in a set of specific disciplinary skills relating to a particular body of knowledge. At later career stages, scientists are better-grounded in a disciplinary approach. The Robert Wood Johnson Foundation Health and Society Scholars program trains postgraduate fellows who address the determinants of health problems across biological, behavioral, environmental, and social levels. Transdisciplinary training at

From the Center for Behavioral and Preventive Medicine, Warren Alpert Medical School of Brown University, and The Miriam Hospital, Providence, Rhode Island

Address correspondence and reprint requests to: Justin M. Nash, PhD, Center for Behavioral and Preventive Medicine, Brown University/The Miriam Hospital, Coro Building, Suite 500, One Hoppin Street, Providence RI 02903. E-mail: Justin_Nash@Brown.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.004

later career stages is disadvantageous when scientists are more fixed in their scientific ways and less open to incorporating new disciplinary approaches into their work.

Early in training at the undergraduate or early graduate levels, a more didactic-intensive approach is used. At the advanced graduate level and beyond, an apprenticeship model is more typical, with mentoring playing a central role in transdisciplinary training. In the single-mentor apprenticeship approach, a transdisciplinary researcher serves as a mentor, and a model, for a student who learns to conduct transdisciplinary research. The single-mentor model in transdisciplinary training is not common.[7–9] The use of multiple mentors is often a necessity because most scientists who can serve as mentors were trained in a single discipline, operate from a single disciplinary framework, and are employed within traditionally structured departments. In this approach, each mentor on the team trains in his or her separate discipline. With a team of mentors, a trainee's proximity to mentors is desirable but not always certain. Mentors can be located within separate departments at the same institution or at separate institutions as part of geographically dispersed networks.[10,11] In this paper, the focus is on training at the advanced graduate and postdoctoral levels, using an apprenticeship model with multiple mentors, to develop scientists who will individually approach research from a transdisciplinary perspective.

Conceptual Understanding of Transdisciplinary Training

The distinction between transdisciplinary training and other integrative training approaches (e.g., interdisciplinary training) is not yet delineated. The distinction in training presented here follows the distinguishing of different integrative research approaches made by Rosenfield[12] and, more recently, Rosenfield and Kessel.[13] They distinguish different integrative research approaches on the explicitness in which the team members integrate disciplinary perspectives and analytic levels. Similarly, it is suggested here that in multidisciplinary training, trainees are taught a single disciplinary approach but also learn to work alongside researchers from other disciplines. The intention of interdisciplinary training, on the other hand, is to develop scientists who possess a working knowledge of different disciplinary conceptual frameworks and methodologic tools. Transdisciplinary training is defined by its intention to produce scientists who are able to synthesize theoretical and methodologic aspects of different disciplines in a defined problem area. The differences in training approaches lie in the presence and level of disciplinary integration involved, with single-disciplinary training and transdisciplinary training anchoring the two extremes.

Constraints and Challenges in Transdisciplinary Training

The challenges in transdisciplinary training extend beyond learning topic knowledge and research skills in different disciplines. The challenges occur at the intrapersonal, interpersonal, and systems levels. In encountering all the challenges, the transdisciplinary trainee confronts some forces that act to push him or her away from engaging in unfamiliar disciplines and other forces that act to pull him or her back into operating solely from the secure, familiar disciplinary fold. In Figure 1, the challenges in transdisciplinary training are presented along with facilitating factors that influence training outcomes.

A Tale of Two Learning Cultures

Obstacles develop when the natural learning style of the transdisciplinary trainee conflicts with the teaching approaches used in different disciplines and at different levels of analysis.[14,15] In their team approach to examining the determinants of cardiovascular health, Gary Berntson, a more basic psychobiological and behavioral neuroscientist, and John Cacioppo, a social psychologist, recognize the challenges in learning to integrate factors across a basic biological level and a social–cultural level.[16] For example, a trainee who is particularly strong in memorizing and reproducing large amounts of factual information may be facile in learning human biology, which is anchored in concrete anatomy and genetics. That trainee could become bewildered when shifting to social psychology, which is based on a complex set of abstractions that represent the interacting actions and influences of relationships among individuals, groups, societies, and cultures. Thus, it is important for transdisciplinary trainees to have a sense of how learning occurs in different disciplines in addition to knowing what needs to be learned. It is especially challenging for trainees to venture into the space that exists between the two disciplines, where the learning and teaching approaches have yet to be established.[17]

Learning Language Within the Learning Cultures

Each disciplinary culture has a language with specialized terminology that allows for efficient communication betweens its members. Success in transdisciplinary training hinges on the capacity of trainees to be able to speak the different disciplinary languages.[2,9,13,17,18] Learning different disciplinary languages is one of the most time-consuming, confusing, and frustrating experiences for trainees. Once successful, however, the transdisciplinary trainee not only learns elements of each language, but is unique in speaking a hybrid language that develops from the core terminology of each disciplinary language. The development of this hybrid language is part of the innovation that occurs in transdisciplinary training and research, along with the development of unique theoretical perspectives and methodologic approaches.

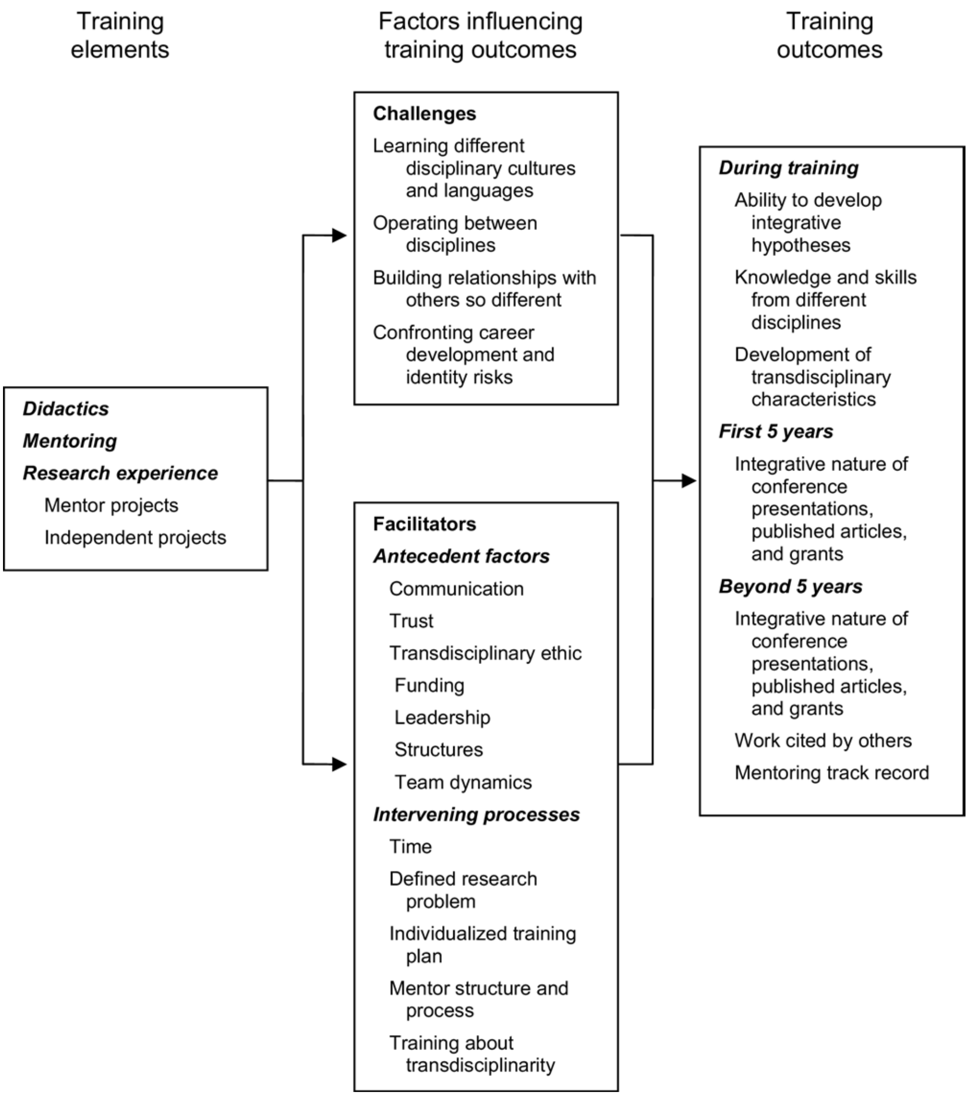


Figure 1. Transdisciplinary training elements, facilitating and challenging factors, and outcomes

Operating in the Ambiguity Among the Disciplines

Transdisciplinary trainees, who are already challenged with learning how to maneuver within separate disciplinary structures, also have to learn how to operate in the ambiguous space between the disciplines.[17] This space is where constructs are ill-defined, methods not yet established, and training objectives unspecified (e.g., topic knowledge, methods, and skills to be learned). This is uncharted territory with terrain that only the trainee traverses. Mentors, who remain comfortably situated within the confines of their respective disciplines, are limited in their ability to guide trainees through the ambiguity existing between disciplines. The trainee, by confronting the unique and complex theoretical and methodologic problems alone, ultimately creates innovative solutions that reflect a synthesis of disciplinary perspectives, a formation of innovative hypotheses, and a creation of new methodologic tools.

Engaging with Unfamiliar Others in an Unsupportive Environment

Effective interpersonal relationships are central to successful collaborative ventures. In transdisciplinary training, relationship-building involves extra challenges. Faculty and trainee relationships that occur across disciplinary lines require engaging with those who not only speak different disciplinary languages but also use unfamiliar scientific approaches and who may harbor a subtle antagonism toward disciplinary approaches other than their own.

The antagonism can be a byproduct of the culture of traditional academic structures that breeds disciplinary stereotyping, prejudice, and rivalry. Traditional academics reinforce narrowly defined disciplines with well-defined boundaries.[1,19] The similarities among the disciplines are not adequately recognized and the differences between them are not well-respected.[20] The situation is further exacerbated by interdepartmental rivalry that occurs as departments compete for finite resources from the parent institution. In the traditional academic environment, faculty and trainees who need support in their efforts to cross disciplinary lines are instead discouraged. Davidson[6] considers the trainee's ability to cross disciplinary, departmental, and institutional divides a critical aspect of transdisciplinary training. As a graduate student in psychology at Harvard, he crossed disciplinary and departmental lines to learn behavioral neurology from scientists at Harvard Medical School and crossed disciplinary, departmental, and institutional lines to learn neuroanatomy from scientists at Massachusetts Institute of Technology.

Confronting Compromises in Career Development and Confusion in Identity

The climb onto and up the academic ladder can leave transdisciplinary researchers feeling misunderstood, undervalued, and without a clearly defined disciplinary identity.[8,9,15,18,21,22] The fundamental dilemma is the perception that the trainee is a jack-of-all-trades but master of none.

After investing extra time to complete formal training, the trainee may face compromised prospects in becoming employed. Individuals trained in transdisciplinary approaches are competitive for positions at the boundaries between disciplines (e.g., positions in comprehensive cancer centers) but are at a disadvantage in seeking specialist jobs within traditional academic departments.

Once hired, transdisciplinary researchers may find that their paths through the academic ranks may not be as swift or smooth as that of their more traditionally trained peers.[1] Transdisciplinary researchers wonder how they will fare in publishing manuscripts and obtaining grants when their theoretical and methodologic work does not reside neatly within any one discipline.[12,13] As transdisciplinary researchers, they face grant and manuscript reviewers who have a natural tendency to be critical of work that is unfamiliar. Davidson,[6] as an individual scientist, and Berntson and Cacioppo,[16] as collaborative scientists, encountered early career challenges in obtaining grant funding because the innovative, transdisciplinary nature of their research was not recognized by review panels representing more traditional disciplines and perspectives. Davidson's experience[6] was that grant reviewers at the time did not recognize that emotions could affect health and were not competent in both biological measures and emotion research.

Even when they secure grants and publish articles, transdisciplinary researchers face hurdles in having their original contributions recognized by members of promotion and tenure committees. Publications that are outside of recognized discipline-specific journals, or that are team-authored, are held in lower regard.[1,12,13] Light and her colleagues[23] at the University of North Carolina note that collaborative cross-disciplinary research frequently requires that five or more authors share credit on important papers. In some cases the co-authors will have contributed almost as much as the first author, yet they receive substantially less recognition.

Factors That Facilitate Overcoming the Challenges

Despite the challenges inherent in transdisciplinary training, formal investments and commitments continue to be made by funding agencies, institutions, professional societies, publishers, leaders, mentors, and trainees. Institutions recognize that transdisciplinary training initiatives can help fertilize interdisciplinary and interdepartmental research, opening opportunities for new funding sources. Identifying the factors that can facilitate the training of transdisciplinary scientists will help to overcome the number of challenges that are present. The factors that are assumed to facilitate transdisciplinary training are, for the most part, based on observational data that have a very small evidence base. In Figure 1, factors that facilitate transdisciplinary training are presented along with the challenges that occur as they influence training outcomes.

Transdisciplinary training often involves a team approach with trainees, mentors, training program leaders, and institutional leaders all central to the process. It is helpful to explicate the factors that facilitate teamwork and team effectiveness. In their contemporary organizational psychology perspective, Kozlowski and Ilgen[24] report that factors that relate to team effectiveness are (1) cognitive processes (e.g., team climate, team mental models, and transactive memory); (2) motivational processes (e.g., cohesion, collective efficacy, group potency); and (3) behavioral processes (e.g., team competencies, functions, and regulatory mechanisms).

Transdisciplinary training functions best when its members capitalize on their own knowledge and expertise, are cohesive and confident, have resources allocated appropriately, and coordinate their collective actions well.[24,25] Problems in training develop when the team members do not have a shared strategic training vision, get derailed from their central focus by conflict, do not learn from their mistakes, and are not supportive of each other. The training team must also be able to anticipate and adapt to the dynamics of the larger multilevel organizational system in which it operates.[25]

Training programs at the University of Wisconsin and at the University of California San Francisco take into account multilevel organizational factors to create an environment that is conducive to transdisciplinary training.[6,26] Training in these programs is flexible and provides access to a wide range of training opportunities (e.g., courses, seminars) and laboratory research experience across many departments. For example, the program at Wisconsin, directed by Davidson,[6] has graduate students in psychology taking courses in neuroanatomy and neurophysiology in the medical school and magnetic resonance physics in the department of medical physics. The training faculty are collaborative in their approach and come from departments with very good interdepartmental relationships.

Consistent with an organizational psychology framework regarding work groups and teamwork, the discussion that follows highlights factors that also relate to transdisciplinary training effectiveness. Some of these factors, termed antecedent factors by Stokols and colleagues,[10,11,27,28] are pre-existing within individuals and institutions. Other factors, termed intervening processes, occur during the training. Figure 1 shows how facilitating factors combine with challenges in transdisciplinary training to influence training outcomes.

Individual-Level Factors

For trainees, mentors, and program directors, the possession of the following characteristics will greatly enhance training effectiveness.

Communication. Confusion and lack of clarity are inherent in the transdisciplinary training process. The ability to communicate is an essential skill for transdisciplinary trainees, mentors, and program directors. Program directors and mentors who communicate clearly with minimal technical jargon help the trainee from becoming confused and frustrated. Understandable communication also facilitates the trainee's ability to learn the language of the unfamiliar discipline. The trainee is responsible for seeking clarification at those inevitable times when there is a lack of understanding. Communicating openly and often is necessary for trainees, mentors, and directors to build all-important trust.

Trust. Trust, an essential ingredient in any close working relationship, is especially critical in the relationships among trainees, mentors, and directors in transdisciplinary training programs. Considering the professional risks assumed and the somewhat speculative nature of the programmatic research undertaken, the trainee must willingly trust in the transdisciplinary training process and in the judgment of mentors and program directors. Trust allows the trainee to expose vulnerabilities associated with not knowing, and to seek information about basic aspects of a specific disciplinary approach. With trust, the trainee is willing to leap into the disciplinary divide, wallow in its uncertainty, and be guided by mentors down a research and career path with an uncertain outcome. The trainee's trust of mentors cannot be blind; some amount of savvy is needed in knowing the role of each mentor and who and when to trust in navigating multiple mentor relationships.

Characteristics consistent with the transdisciplinary ethic. There are core characteristics involving attitudes and behaviors that reflect an ethic that allows trainees, mentors, and program directors to navigate the transdisciplinary research and training process.[2,12,13,22,27] The characteristics (Table 1) provide protection from becoming parochial about a trainee's primary discipline and from regressing back to what is familiar. They keep the trainee from becoming too discouraged when confronting multiple challenges and when tangible rewards are not immediately apparent. The characteristics are important for learning to participate in and lead collaborative teams.

Table 1. Characteristics consistent with the transdisciplinary ethic

Openness and respect for different disciplinary approaches
Desire to work in collaborative teams involving multiple disciplines
Broad-gauged contextual thinking
Interest in using multiple methodologic tools
Intellectual curiosity and willingness to take intellectual risks
Tolerance for uncertainty
Self-assuredness and non-defensiveness when not knowing
Assertiveness in seeking clarification
Optimism, tenaciousness, and willingness to operate without clear, immediate rewards
Ability to lead and foster mutual respect and trust in others

Funding Agency and Training Institution-Level Factors

Funding. Funding agencies are essential in dedicating dollars to transdisciplinary training for building and maintaining a training infrastructure, supporting trainee stipends, funding faculty to develop and implement specialized curricula, and evaluating program effectiveness. The National Cancer Institute (NCI)'s Cancer Education and Career Development Program (NCI R25T) mechanism is an excellent example of support for developing innovative transdisciplinary training structures and curricula. Funders can be helpful by actively working with training directors to ensure that the training does not regress to the confines of individual disciplinary approaches.[2]

Training program leadership and institutional structures. The presence of an influential, strong, and committed training director is critical to the success of a transdisciplinary training program.[2,3,11,13] The most effective training directors are those who are well-respected, trusted, and convincing in communicating a shared vision to all stakeholders, including institutional administrators, research faculty, mentors, and trainees. Effective directors build and maintain the training structures as well as manage the training processes. Maintaining an awareness of the system dynamics and implementing measures for problem prevention and resolution are important in protecting the most vulnerable training resource, the trainee.

Within the institution, designing physical space, structuring academic operations, and creating incentive structures for cross-disciplinary science are essential for fostering cross-disciplinary learning and collaboration.[13,19] Factors found to enhance science integration—and the likelihood of the serendipitous development of innovative ideas between trainees and mentors—include proximity of research space among collaborators, streamlined administrative arrangements, and a history of collaborations between participating departments that are closer in disciplinary scope.[10,11,13,15,27] It may be necessary to physically and structurally separate research and training centers from traditional departments instead of trying to overcome the impediments to transdisciplinary training that exist in traditionally structured institutions.[18] Davidson[6] notes that at Wisconsin he has the advantage of having the medical school and campus-based departments in close proximity.

Intervening Processes During Training

Separate from the antecedents that are in place prior to training, intervening processes during training can help the trainee to feel respected, valued, and supported; keep the training process on course; and counteract the natural tendencies to regress to the familiar disciplinary approach.[10,11]

Time. The availability of adequate time is necessary for the transdisciplinary training structure and process to develop.[17,27] Time allows for effective communication to occur, trusting relationships to build, different disciplinary languages to be understood and spoken, transdisciplinary values to develop, and theoretical knowledge and methodologic skills in other disciplinary approaches to be learned. One example of protecting time for transdisciplinary training is the NCI Cancer Prevention Fellowship Program's providing scientists release time from other duties so they can engage in training activities for fellows.[8] A second example is the NCI R25T funding mechanism, which provides partial salary support for investigators to create innovative transdisciplinary curricula. An initial investment in time will enhance the quality of the outcomes and eventually yield a savings of time once the transdisciplinary structure and processes are in place.

Defined research problem and an individualized training plan. Wallowing in uncertainty is inherent in the transdisciplinary learning process. Guarding against unnecessary wallowing is important so that the trainee is able to avoid prolonged aimlessness and lack of development. Two keys to ensuring progress toward training goals are (1) focusing training on addressing a specific research problem, rather than trying to indiscriminately master all theoretical and methodologic aspects of each disciplinary approach, and (2) maintaining a reasonably limited disciplinary scope in training.[13,18,22]

A clearly defined research problem helps to anchor the trainee's programmatic research development and the transdisciplinary training process. The research problem also orients the training director, mentors, and trainee in developing an individualized training plan. In defining the research problem and the disciplinary scope of training, the horizontal and vertical disciplinary integrations should be complementary and balanced.[10,27] A trainee who is being trained across disciplines that are too divergent can feel fragmented and polarized, which intensifies the pull back into the familiar disciplinary approach.[27] If a trainee's program is too narrow in disciplinary focus, potential innovation can be suppressed.[18]

An individualized training plan can be used to map the training process and content around the defined research problem.[22] Table 2 outlines the components of an individualized training plan.

Table 2. Components of an individualized training plan

I. Trainee
II. Programmatic research objective
III. Mentoring team
- A. Primary mentor
- B. Secondary Mentor 1
- C. Secondary Mentor 2
- D. Advisor

IV. Competencies to attain
- A. Transdisciplinary training and research process
- B. Content knowledge (Discipline 1, Discipline 2, Discipline 3)
- C. Research methods (Discipline 1, Discipline 2, Discipline 3)
- D. Manuscript writing
- E. Grantsmanship/grantwriting
- F. Research ethics

V. Methods to attain competencies
- A. Didactics
  1. Courses
  2. Seminars
  3. Journal clubs/brown bags
- B. Mentored research experiences
  1. Mentor projects
     - a. Primary mentor project (project aim, trainee role)
     - b. Secondary Mentor 1 projects (project aim, trainee role)
     - c. Secondary Mentor 2 projects (project aim, trainee role)
  2. Independent research projects (project aims, trainee roles)

Mentoring structure and processes. In transdisciplinary training, students can benefit enormously from the team-mentoring structure, with each mentor representing a different discipline.[6] Team mentoring provides a breadth of experience that is unattainable through any single mentor. In team mentoring, each mentor helps the trainee to learn the content and skills of a particular disciplinary approach. In addition, each mentor also has a responsibility to help the trainee shift in and out of each discipline and work in the space between the disciplines. A mentor within the trainee's primary discipline has the responsibility of helping the trainee to move the beyond the discipline. A mentor in a complementary discipline has the responsibility of ensuring that the trainee is receiving relevant and sufficient coverage of that discipline's approach.

Frequent meetings, both scheduled and impromptu, are important. Regular meetings among members of the mentoring team and training directors keep the training process coordinated so that everyone works toward the stated objectives in the training plan. In situations where individuals involved in training lack proximity, reliance on telecommunications and other forms of electronic technologies helps to maintain as much contact as possible. Kaplan at Wake Forest University and Manuck at the University of Pittsburgh[5] do not let being at different institutions impede their communication. They take advantage of technologic advances in communication to stay in regular contact and to seamlessly exchange data and manuscripts. They note that they probably spend as much time in contact with each other as either does with his colleagues at the same institution. There is no substitute, however, for face-to-face contact.[29]

Meta training about the transdisciplinary research and training process. The training process can be explicit in helping the trainee understand how to manage the unique aspects and challenges of engaging in transdisciplinary training. Training can include helping the trainee to (1) understand the conceptual distinction of transdisciplinary training; (2) learn how to manage the obstacles and capitalize on the facilitators existing at the institutional, program, and individual levels in transdisciplinary training and research; (3) manage the unique career-development challenges related to securing academic jobs, funding, publication, promotion, and tenure; and (4) develop strategies to facilitate shifting in and out of disciplinary frameworks and working between frameworks that are paradigmatically different. The program can help the trainee to know the cultural and instructional styles of the different disciplines and how well they intersect with the trainee's own learning style. The knowledge and skills related to transdisciplinary training and research can best be developed through a combination of formal didactics, research experiences, and mentorship.

Future Directions

There is much written but little known empirically about training across disciplines. There is an opportunity to (1) develop a better understanding of the operational distinctions of different integrative training approaches, (2) empirically determine the effective elements of transdisciplinary training models, (3) define the outcome metrics appropriate at different time frames, and (4) create toolkits to help with training process and administration.[10,11]

Table 3. Indications of transdisciplinary qualities in scholarly products

Transdisciplinary scope of the research topic and its conceptualization
Diversity of research methods used in the study
Contextual scope of the author's conceptualization of the research topic
Hypotheses generated that synthesize theoreticaltheoreticalalal frameworks from different disciplines
Levels of analysis bridged
Co-authors from different disciplines

Note: Adapted in part from Mitrany and Stokols[15]

Making Operational Distinctions Among Conceptually Different Forms of Integrative Training

Multidisciplinary, interdisciplinary, and transdisciplinary training have different training objectives. There is yet no clear articulation of how the various training approaches differ in structures, methods, or processes to achieve the different objectives. Nor is it known what specific elements of training are critical to the transdisciplinary trainee's being able to synthesize theoretical and methodologic aspects of different disciplines.

Empirically Identifying the Effective Elements of Transdisciplinary Training Models

There have been few empirical efforts that examine the transdisciplinary training process and outcome.[11,15,22,30] The development of theoretically based qualitative and quantitative methodologic approaches is needed to identify (1) essential individual characteristics in trainees, mentors, and program leaders; and (2) key institutional qualities, training structures, and processes that relate to training success.

Defining the Metrics and Time Frames of Outcome

The ultimate determination of success will be the eventual impact that trainees have as scientists who use integrative theoretical perspectives and methodologic approaches to improve the nation's health. At present, the more immediate focus can be on evaluations of the quality, novelty, and scope of the disciplinary integration in the trainees' work at different time points during and following training.[10,11,15,21] Figure 1 displays some of the outcomes that can be considered at different time points. Outcome assessments can build on the initial work of Stokols and Rosenfield.[11,15] Table 3 lists criteria that can be considered indicators of disciplinary integration. Also needed is the establishment of other indicators of program effectiveness beyond trainee performance, such as the performances of the mentors and the effectiveness of the program.

Developing Training Toolkits

A greater empirical understanding of transdisciplinary training processes and outcomes can help inform the development of training toolkits.[11] Training toolkits can contain materials to be used by training directors for multiple purposes, including training and evaluation. Examples of toolkits used for training purposes include (1) helping the trainee to understand the uniqueness, challenges, and the processes of transdisciplinary training and research; (2) helping the trainee to develop some of the essential transdisciplinary values and skills competencies; and (3) guiding mentors in training transdisciplinary scientists, especially mentors who work with trainees outside their primary discipline. Examples of toolkits used for evaluation purposes include (1) audits of training readiness to assess the presence of transdisciplinary characteristics in prospective trainees,[11] (2) audits of mentoring readiness for potential mentors, and (3) assessment methods and measures to monitor ongoing processes in transdisciplinary training and to evaluate outcomes. Toolkits used for evaluation purposes will benefit from the development of common definitions and standards of what constitutes adequate evidence.

This is an exciting time in the evolution of science and the training of scientists. Disciplinary integration is increasingly called upon to address the complexities of health problems. The integration of disciplinary research creates new hybrid disciplines (e.g., genetic epidemiology) and, in a reciprocal way, influences the way disciplinary science is conducted. Today's transdisciplinary training has great potential to affect tomorrow's mentoring models in innovative ways. Now is the time for the scientific community to take action to better delineate the different integrative training approaches, identify their effective elements, and determine their long-term impact.

No financial disclosures were reported by the author of this paper.

References

1. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: National Academies Press, 2005 www.nap.edu/catalog.php?record_id=11153#toc.
2. Morgan GD, Kobus K, Gerlach KK, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003;5(1S):S11–9.
3. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006;33:515–31.
4. Kessel F, Rosenfield PL, Anderson NB, Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
5. Kaplan JR, Manuck SB. Status, stress, and heart disease: a monkey's tale. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
6. Davidson RJ. Affective neuroscience: a case for interdisciplinary research. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
7. Abrams DB, Leslie F, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res 2003;5(1S):S5–10.
8. Chang S, Hursting SD, Perkins SN, Dores GM, Weed DL. Adapting postdoctoral training to interdisciplinary science in the 21st century: the Cancer Prevention Fellowship Program at the National Cancer Institute. Acad Med 2005;80:261–5.
9. von Ruschkowski E. Changes in the world of science: the realities of interdisciplinary training. Science, 2003. sciencecareers.sciencemag.org/career_development/previous_issues/articles/2170/changes_in_the_world_of_science_the_realities_of_interdisciplinary_training.
10. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
11. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
12. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
13. Rosenfield PL, Kessel F. Closing commentary: fostering interdisciplinary research: the way forward. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
14. Bradbeer J. Barriers to interdisciplinarity: disciplinary discourses and student learning. Journal of Geography in Higher Education 1999;23:381–96.
15. Mitrany M, Stokols D. Gauging the transdisciplinary qualities and outcomes of doctoral training programs. J Plan Educ Res 2005;24:437–49.
16. Berntson GG, Cacioppo JT. A contemporary perspective on multilevel analyses and social neuroscience. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
17. Kahn R, Prager D. Interdisciplinary collaborations are a scientific and social imperative. The Scientist 1994;8:12.
18. Rhoten D. Interdisciplinary research: trend or transition. Items & Issues, Soc Sci Res Council (SSRC) 2004;5:6–11.
19. Kafatos FC, Eisner T. Unification in the century of biology. Science 2004;303:1257. doi: 10.1126/science.303.5662.1257.
20. Whiteley BE, Kite ME. The psychology of prejudice and discrimination. Belmont CA: Thomson Wadsworth, 2006.
21. Klein JT. Crossing boundaries: knowledge, disciplinarities and interdisciplinarities. Charlottesville VA: University of Virginia Press, 1996.
22. Nash JM, Collins BN, Loughlin SE, et al. Training the transdisciplinary scientist: a general framework applied to tobacco use behavior. Nicotine Tob Res 2003;5(1S):S41–S53.
23. Light KC, Girdler SS, Hinderliter AL. The risk of hypertensive heart disease: the joint influence of genetic and behavioral factors. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
24. Kozlowski S, Ilgen D. Enhancing the effectiveness of work groups and teams. Psychological Science in the Public Interest 2006;7:77–124.
25. Marks M. The science of team effectiveness. Psychological Science in the Public Interest 2006;7:i.
26. Chesney MA, Coates TJ. The evolution of HIV prevention in San Francisco: a multidisciplinary model. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
27. Fuqua J, Stokols D, Gress J, Phillips K, Harvey R. Transdisciplinary collaboration as a basis for enhancing the science and prevention of substance use and "abuse." Subst Use Misuse 2004;39:1457–514.
28. Stokols D, Grzywacz JG, McMahan S, Phillips K. Increasing the health promotive capacity of human environments. Am J Health Promot 2003;18:4–13.
29. Seeman TE. Integrating psychosocial factors with biology: the role of protective factors in trajectories of health and aging. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
30. Rhoten D, Parker A. Education: risks and rewards of an interdisciplinary research path. Science 2004;306:2046.

The Social Determinants of Cancer

A Challenge for Transdisciplinary Science

Robert A. Hiatt, MD, PhD, Nancy Breen, PhD

Abstract: To make further significant advances in cancer control research, a transdisciplinary science approach is needed that integrates the study of the biological nature of cancer and its clinical applications with the behavioral and social influences on cancer. More-effective interventions to reduce the burden of cancer can be developed and implemented by the adoption of a transdisciplinary research framework that takes into account the social determinants of cancer and seeks to discover interactions among social, environmental, behavioral, and biological factors in cancer etiology. This paper addresses two critical issues in the science of team science: (1) a cross-disciplinary, multilevel framework for organizing future research, and (2) a perspective that could aid in the translation and dissemination of cancer research findings in health care and public health practice. This conceptual framework is designed to encourage transdisciplinary research that will integrate social determinants into cancer research. The authors' goal is to promote a more complete understanding of the causes of cancer that will lead to the improved translation and implementation of the results of research.
(Am J Prev Med 2008;35(2S):S141–S150) © 2008 American Journal of Preventive Medicine

Introduction

Cancer is a group of diseases that impose a heavy burden on the public health and pose a challenge to science. While the century-long trend of increasing cancer mortality in this country was reversed in the mid-1990s, cancer remains the second leading cause of death,[1] the toll on human suffering is profound, and its economic costs to society are substantial.[2] Furthermore, cancer presents an intellectually complex set of problems because of multiple sites and causation, inadequately understood biology, and myriad intervention strategies. Impressive progress has been made against cancer, but not solely because of new knowledge about its genetics and molecular biology or new therapeutic approaches. Progress has also followed in the footsteps of understanding the social and behavioral determinants of cancer.

To make further significant advances in cancer control research, a transdisciplinary approach is needed that integrates the study of the biological nature of cancer and its clinical applications with the behavioral and social influences on the disease. Cancer research is an example of how the complexities of modern science require teams of investigators from many disciplines.[3] Transdisciplinarity is a process in team science in which members share conceptual and methodologic frameworks to integrate concepts from their own disciplines with those of other scientists to solve a particular problem at hand; in doing so, they develop new concepts and perspectives that go beyond their own disciplines.[4–8] It differs from a multidisciplinary approach in which groups of scientists independently or sequentially apply their own disciplinary perspectives to a problem, and from an interdisciplinary approach in which scientists are integrated as a team but still work independently from their own disciplinary perspectives. The unexpected and novel insights generated by transdisciplinary science come from a truly integrated team approach in which scientists are willing to hold their own knowledge lightly and to seek new perspectives from interaction with others. Examples of successful transdisciplinary science can be found in the fields of bioengineering, environmental economics, space science, meteorology, and others.[9–11] It can be argued that taking a cells-to-society approach in cancer control science means that more-effective interventions can be developed and implemented to reduce the burden of cancer. To accomplish this, the perspective advanced by the IOM and others that uses a socioecologic model is supported by the authors.[3,12]

The socioecologic model or perspective implies reciprocal causation between the individual and the environment that essentially defines interactive ef-

From the Department of Epidemiology and Biostatistics, Helen Diller Family Comprehensive Cancer Center, University of California San Francisco (Hiatt), San Francisco, California; and the Applied Research Program, Division of Cancer Control and Population Sciences, National Cancer Institute (Breen), Bethesda, Maryland

Address correspondence and reprint requests to: Robert A. Hiatt, MD, PhD, Department of Epidemiology and Biostatistics, University of California San Francisco, 185 Berry Street, Suite 5700, San Francisco CA 94143-0981. E-mail: rhiatt@cc.ucsf.edu.

doi:10.1016/j.amepre.2008.05.006

fects.[13] First developed to explain human behavior within society,[14] this model has been increasingly applied to broaden the understanding of health issues.[15] However, to fully operationalize the socioecologic model and concepts like the web of causation[16] and embodiment,[12] a range of scientific perspectives is required. Transdisciplinary cancer control research provides a framework for bringing the interdisciplinary range of scientists together so that they can study and analyze the wide range and types of inputs located at various levels (from cells to society). The goal of transdisciplinary science is to yield a detailed and vivid snapshot of the impact of the web of causation and to rationalize interventions at various critical points in the resulting picture.

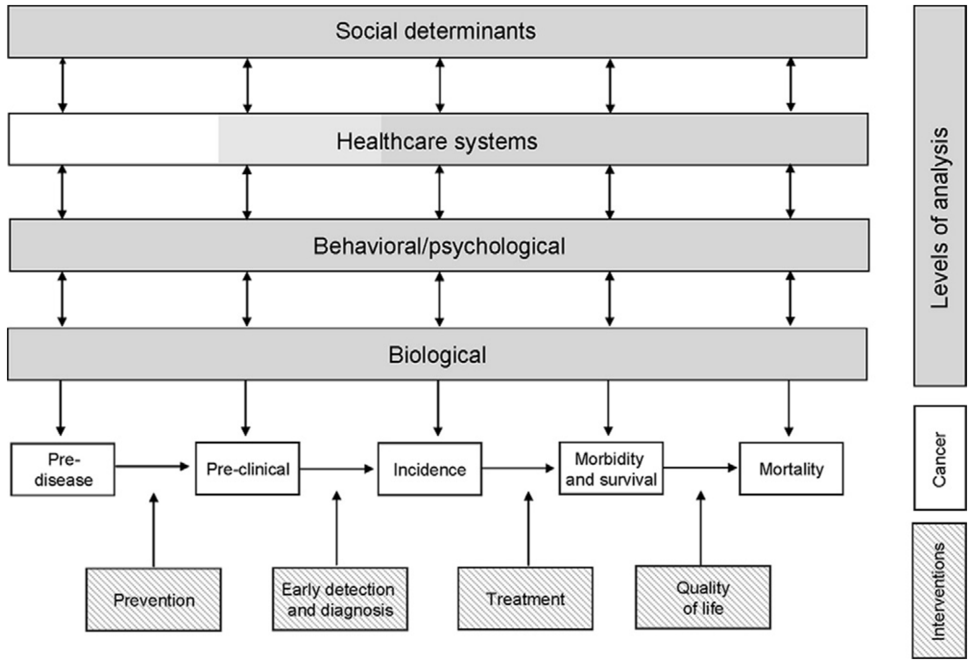


Figure 1. Social determinants of cancer. Framework illustrates how social determinants relate to other levels of analysis and types of interventions along the cancer continuum. Healthcare systems are less likely to influence cancer incidence than mortality and are lightly shaded in the preclinical phase of the continuum.

The authors' definition of social determinants encompasses social and economic conditions such as poverty, the conditions of work and healthcare delivery; the chemical toxicants and pollutants associated with industrial development; and the positive aspects of human settlements that make active living and healthy eating possible. The socioecologic model incorporates and augments discoveries in cancer biology and clinical oncology, in addition to those from the social sciences. A key question in cancer research is why social determinants are important: Is it because of their indirect effects through individual risk factors or behaviors, like smoking; because they interact with genetic and other biological factors (e.g., gene–environment interactions); because they are direct and irreducible causes of illness regardless of intervening variables[3,17]; or because of all these reasons? Krieger[18] has recently proposed the banishment of the terms *proximal* and *distal* to emphasize the importance of avoiding linear causal thinking and to consider how social determinants might act across non-adjacent levels.

Two critical issues in the science of team science are addressed in this paper[7]: (1) a cross-disciplinary, multilevel framework for organizing future research, and (2) a perspective that could aid in the translation and dissemination of cancer research findings in health care and public health practice.[3,4] This conceptual framework (Figure 1) is designed to encourage transdisciplinary research that will integrate social determinants into cancer research. The goal is to promote a more complete understanding of the causes of cancer, leading to the improved translation and implementation of research results.

Framework

This framework is designed to aid in conceptualizing how social determinants interact with other factors in the etiology of cancer and to capture changes over time. It begins with the cancer continuum,[19] adds levels of analysis,[20–22] and considers the impact of interventions along the continuum.[23,24] It draws on the grid elaborated by Krieger[25] to distinguish domains of social inequality across the cancer continuum. Throughout, the need is stressed for a transdisciplinary approach to bring these concepts together. This framework invites researchers from all disciplines to engage in cancer research within the context of its social determinants as part of the "bold experiment" of transdisciplinary research.[26]

The Cancer Continuum

The cancer continuum forms the horizontal axis for the framework and illustrates the course of cancer from disease-free through preclinical early cancer to diagnosis, to survivorship, and to end-of-life and death.[19] Each phase is influenced by different factors in the social environment, and together they incorporate a life-course approach. Different disciplines usually focus on different stages of this continuum, but the authors contend that a transdisciplinary approach that considers and integrates research questions and findings all along this continuum and over the life course could yield more valuable scientific outcomes.

Multiple Levels of Analysis

The concept of *levels of analysis* used by Anderson[27] forms the basis for elucidating social factors that influence cancer incidence and mortality. A healthcare level[28] influenced by social forces and critical to cancer outcomes has been added. Multiple additional levels could be introduced into this framework (as has been done in other models[29]) as they are needed to highlight specific research approaches or pathways (e.g., the physical environment). For simplicity, four levels have been selected. First, the focus is on broad social conditions and policies; second, on the impact of healthcare systems; third, on behavioral and psychological factors; and finally, on the biological mechanisms of carcinogenesis. Interventions to reduce disparities and the burden of disease may be introduced at any of these levels.

Although this framework represents these relationships as a simple, linear process, they are neither simple nor linear.[30] Complex, multidirectional interactions link biological, clinical, and broader social influences into a web of causation.[16,18] For example, biological factors can influence behavior and generate a need for healthcare interventions. Also, policies and legislation concerning coverage for health care can shape individual behaviors and the use of clinical services. This complex, multidirectional interaction of social determinants with other levels challenges researchers working in all areas of cancer investigation to consider the specific pathways and mechanisms that might link their results to fundamental causes. Because cancer involves the complete spectrum of scientific endeavor from genes to society, a transdisciplinary research perspective may be the best approach for understanding the complex, multilevel causal mechanisms and pathways needed to inform cancer control interventions and policies.

Social Determinants

Social determinants have been called the fundamental causes of health and disease,[31] and this is how the term is used here. They are also characterized as the *upstream* or *distal* social, environmental, economic, and cultural factors that shape or determine individual and group behavior.[32–34] In the framework, social determinants include the physical and built environment that are part of or the result of human activity. Krieger[25] enumerated the key social determinants of cancer in her grid. Others also have discussed how fundamental causes and upstream events influence population health.[33,35–37] Although associations between social determinants and population health outcomes may sometimes appear self-evident, few causal relations have been rigorously established.

Understanding how resources and forms of discrimination are distributed in the population is key to understanding fundamental causes. Common measures of socioeconomic resource distribution include occupation, income, wealth, poverty, debt, employment status, education, and health-insurance coverage. Discrimination occurs on the basis of race, gender, age, sexual orientation, and other factors. These distributions can be measured at various levels (e.g., individual, community, county, state, national). Clearly these fundamental causes affect a broad range of health outcomes (e.g., cardiovascular diseases, diabetes, cancer), and a strong case has been made for shifting from the traditional NIH disease-specific approach to an approach that considers the multiple outcomes of common causes.[3] Yet much can be learned by focusing on a particular disease as long as researchers recognize that the social determinants of that disease may have other downstream health consequences.

Examining the distributions of social determinants at various levels across the cancer continuum exposes nonrandom patterns of cancer-related behaviors and outcomes among groups or individuals that may inform key biological mechanisms or be influenced by them.[38] The transdisciplinary research task is complex, and will require teams of scientists willing both to teach aspects of their disciplines to scientists in other fields and to engage in the painstaking task of formulating new conceptual models more appropriate to the problem. However, such a transdisciplinary approach may be just what is needed to realize cancer control objectives, such as those in *Healthy People 2010*.[39,40]

The Role of the Healthcare System in Cancer Incidence and Mortality

The relative importance of health care versus social-level factors has been hotly debated in the population health literature.[33,41,42] A challenge for cancer control research is to clearly distinguish outcomes that are due to deficiencies in healthcare delivery from those external to it, so that interventions can be appropriately targeted. Although it might not be the case in an ideal health system in which due attention is paid to prevention as well as clinical services, in current-day practice the evolution of cancer is less likely to be influenced by health care prior to screening and clinical diagnosis than it is later in the cancer continuum. Cancer has a preclinical phase that begins when cancer can be prevented and extends through its initiation until detection. During the preclinical phase, access to health care can affect the progression of cancers for which early-detection procedures are available (i.e., breast, cervix, colon, prostate), but overall this access is less likely to influence cancer incidence (and is thus lightly shaded for emphasis in the framework).[17] To understand social gradients and racial and ethnic inequalities in incidence, the broader social determinants of cancer—beyond the usual scope of medical care—must be explored.

Cancers, Not Cancer

A critical point is that cancer is actually many different diseases with different etiologies. The social environment may affect these different types of cancer in different ways. Cancer registries currently report approximately 80 types of malignant neoplasm, and define them by their location and cell types.[43] However, four sites account for approximately one half of all cancer incidence: Breast (15%); prostate (17%); lung (13%); and colon (8%) cancers accounted for 52% of all estimated new cancer diagnoses in 2006.[44] The concentration of cancer incidence among these four sites provides an opportunity for site-specific inquiry into the social determinants of cancer. For example, lung cancer mortality is strongly associated with tobacco use and social policies. Breast and colon cancer mortality is shaped by the distribution of screening in the population. Even though breast cancer incidence is more common in higher-SES women, mortality is higher among lower-SES women.[45,46] There are also important differences in incidence by race and ethnicity in different cancer sites. While Vietnamese and Hispanic women have some of the lowest rates of breast cancer incidence, they have the highest rates of cervical cancer incidence.[47] Thus, cancer offers some paradoxes and evokes research questions that may shed light on the various ways that social determinants affect cancer outcomes.

Measuring Disparities in Cancer Incidence and Outcomes

Cancer Registries

Cancer is unique among the chronic diseases in having long-standing population-based registries. Since the early 1970s, cancer registries have abstracted medical records, pathology, surgery, hospital, and outpatient clinic records on cancer incidence, survival, and mortality.[43] Registry data have been the main source of questions raised about cancer–health disparities. However, registries have lacked the data necessary to fully answer these questions on the SES of cancer cases. The first linkage between surveillance, epidemiology, and end result (SEER) registry data and areal SES data was published in 1980.[48] Currently, SEER registry cases are routinely geocoded and linked to county-level census data on SES (seer.cancer.gov/seerstat/variables/countyattribs/). Areal socioeconomic data can supply a proxy for individual SES or provide information about the context in which an individual resides, such as neighborhood or county characteristics.[22,49,50] Advances in information technology, linkage methods, and improved data systems can deliver tools to improve the value of cancer registration to understanding social determinants within the context of a transdisciplinary approach to cancer research[51]; however, political action will be needed to actualize that potential.

Socioeconomic Gradients in Cancer

Socioeconomic gradients in health and mortality are well-documented, although this relationship for cancer does not appear to be as strong as for cardiovascular disease.[52–55] Analyses of linked cancer registry and county-level census data have been used to document gradients and disparities for mortality, survival, and incidence.[45] Linked databases have also allowed researchers to examine the effect of SES factors on individuals in the contexts in which they live and work,[56,57] by cancer stage,[22] and for other diseases.[58]

At the population level, if socioeconomic gradients in cancer incidence and outcomes persist after adjusting for known risk factors (e.g., tobacco use and other risky behaviors) and for screening, that finding would provide empirical support for the value of seeking direct biological pathways between the adverse conditions associated with lower SES and cancer. A recent study compared health outcomes for which prevention and therapeutic interventions are available to outcomes for which they are not, and found stronger SES gradients for outcomes with proven interventions.[17] The authors concluded that the underlying fundamental cause has to do with the set of resources widely accessed by people with higher SES, although this explanation continues to be debated, as discussed in the next section. Nevertheless, the broad range of the social determinants of cancer underscores the need for transdisciplinary studies to parse out the roles that biology, individual behaviors, and social determinants play in shaping SES gradients in specific cancer sites.[6,51]

Multilevel Influence of Social Determinants on Cancer

Observed disparities in cancer mortality, survival, and incidence have motivated the study of social-level influences on the etiology of cancer. The development of social epidemiology within the field of epidemiology opened the way for multilevel analysis in cancer control. The overall framework proposed in Figure 1 is designed to encourage thinking about how different disciplines can contribute to solving the challenge of cancer–health disparities. Traditionally, population health and social factors have been the focus of epidemiologists, sociologists, economists, anthropologists, political scientists, and systems theorists. Health care has been the purview of health services researchers, economists, behavioral and communications scientists, and clinicians. Individual human behaviors or risk factors that mediate health have been the realm of psychologists and behavioral scientists. The basic science disciplines of genetics, cell biology, immunology, and biochemistry have elucidated biological pathways and mechanisms. The task is finding ways to bring together two or more of these levels. Few biologists, for example, have yet addressed questions concerning how social factors "get under the skin" and result in cancer.

Social level. An active area of research is the influence of broad upstream factors on the political economy.[33,59,60] As noted already, making causal links with disease is most difficult at the level of fundamental causes. Ecosocial theory offers a useful conceptual model for linking fundamental causes and individual health, especially when combined with the core concept of "embodiment" that holds that bodies absorb, process, and reflect the conditions of human existence because people are both biological organisms and social beings.[61]

Many studies of broad social forces have raised concerns about the unhealthy side effects of production for profit. For example, the use of chemical fertilizers to improve yields of food may lead to environmental contamination with potentially carcinogenic agents.[62] Highly caloric processed foods are profitable but have little nutritional value.[63–66] In short, substantial health costs are associated with food production in the U.S.[67] The recognition of these unmeasured costs (as well as those incurred from natural-resource depletion) has led some economists to suggest that the sustainability and quality of life should be evaluated when the value of production is computed.[68] Much as ecosocial theory offers a new perspective for epidemiology, these economists have created a new approach to economics called *ecologic economics*, which addresses the interdependence and co-evolution between human economies and natural ecosystems. Many ecologic economists refer to this new field as a transdiscipline rather than a conventional discipline.[69,70]

Both the physical and built aspects of the environment influence cancer outcomes.[71] The physical environment influences both behavior and biology, and may help explain some observed trends and disparities in cancer incidence and outcomes. For example, minorities and lower-income groups face higher levels of exposure to environmental hazards, including industrial facilities, waste-treatment sites, or waste-disposal sites.[72] The effect of environmental risk factors on cancer in humans is hard to assess, especially because few data on carcinogens are available and specific long-term exposures on individuals and populations are not monitored.[73] The unequal distribution of environmental hazards has spawned an environmental justice movement[74] as well as discussion and debate on how to best measure and evaluate the impact of environmental hazards.[75]

The important policy issues that this social-level research has generated involve trade-offs between public health and economic profitability. Policy solutions require expertise from urban planning, engineering, law, economics, political science, and the biomedical disciplines as well as informed community input. Political decisions and economic incentives shape the built environment through zoning, construction investment, pollution limitations, available park and recreation areas, and the effectiveness of policing. The built environment, in turn, shapes community choices relevant to health, including cancer. For example, sidewalks or paths that lead to safe and desirable destinations for walking and cycling can increase physical activity.[76] Physical activity, in turn, is significantly associated with reduced colon-cancer mortality,[77,78] and is indirectly associated with lower mortality for many other cancers through reducing overweight and obesity.

Some groups, including those who are poor, black, Hispanic, or Native American, are more likely to experience overweight and obesity than the general public. They are also likely to reside where physical activity is more difficult, fruits and vegetables are less accessible, and tobacco and alcohol are prevalent.[79–81] In this way, residential segregation is another fundamental cause of racial disparities in health.[82]

Healthcare-delivery level. The impact of health care on cancer is related to insurance coverage, quality of care, and timely access to that care. Insurance, the financing mechanism used to pay for most health care in the U.S., may be the most important factor shaping health disparities.[83] Even after adjusting for sociodemographics, risk factors, morbidity, and self-rated health, the lack of health insurance is still linked to higher mortality.[84] Between 2000 and 2005, health insurance premiums grew by 73% (compared with cumulative inflation of approximately 14% and cumulative wage growth of 15%), and the percentage of employers offering health benefits fell from 69% to 60%.[85] From January through September 2006, 43.8 million people of all ages (16.9%) were uninsured,[86] and coverage rates varied substantially by race, ethnicity, and socioeconomic position. However, most cancer occurs in people aged ≥65 years, and only 7% of the individuals facing a new diagnosis of cancer were uninsured (approximately 86,000 in 1997).[41]

Although most people in the U.S. eventually obtain the necessary medical treatment, some do not receive it in a timely manner.[87,88] Without insurance coverage and a system to provide continuous care, patients must negotiate and pay for each step in their health care.

The President's Cancer Panel[42] has documented barriers to care that include elements inherent in the system (e.g., fragmentation of care); finances (e.g., lack of insurance or underinsurance); and physical environment (e.g., excessive distance from or physical barriers to accessing treatment facilities) as well as information and education barriers (both provider- and patient-related) and issues of cultural insensitivity and bias.[42]

Even with equal access, there is no guarantee of equal quality or use of services. Poor transportation, the lack of sick leave and time-off from work, and the need to supply child- and elder-care may pose insurmountable barriers to the optimal use of health care for people of low income and education.[89–92] Persistent racial, ethnic, and age differences in the receipt of primary therapy, conservative therapy, and adjuvant therapy provide indirect evidence of racial, ethnic, and age bias in access.[93–96] Improving the quality of care for cancer patients of all sociocultural backgrounds will require a major restructuring of the delivery of cancer care and the continuous monitoring of quality improvement and accountability.[41]

Behavioral/psychological level. Behaviors are often the mediating steps between social determinants and cancer outcomes. Behaviors long-recognized as important contributors to cancer include tobacco and alcohol use, poor diet, physical inactivity, high-risk reproductive behavior, and occupational hazards.[97] The mechanisms linking social-level factors, individual behaviors, and biology with cancer incidence and mortality are reasonably well-understood for tobacco, and the transdisciplinary research being conducted in tobacco control can serve as a model of how such research could be conducted for other cancer sites.[98] However, transdisciplinary research is still needed to elucidate the pathways and relationships of causation for those other sites.

Linkages between individual behaviors and fundamental causes have been posited, but the ability to demonstrate causation has been limited by cross-sectional data and linear statistical methods. Risk regulators, the range of intermediate factors that constrain or promote individual choice, have been posited as conceptual bridges linking fundamental causes and individual behaviors.[99] The concept of risk regulators locates individual choices within the broader social context of fundamental causes in order to provide testable hypotheses of association for multilevel transdisciplinary empirical research.

Individual behavior related to tobacco is intimately tied to the social context; social-level interventions to control tobacco are more effective than approaches addressing individual behavior.[100–102] Much of the success of tobacco-control efforts has come from changes in social policies such as federal excise taxes, workplace bans on smoking, media campaigns, clean-indoor-air policies, and the enforcement of restrictions on tobacco use by minors.[103,104]

Tobacco-control research is probably the best current model for effective transdisciplinary science, as it has grown from a focus on individual human behavior to include the understanding of the genetics of tobacco addiction, the distribution of smoking habits in the population, and how these complex relationships are affected by social policy.[105] Stokols and colleagues[106] evaluated the collaborative processes and the scientific and public-policy outcomes of the transdisciplinary approach used in one large tobacco control effort funded by the National Cancer Institute (NCI), and concluded that there was "progress toward intellectual integration" over the course of the initiative. However, methodologic challenges remain regarding how to evaluate large-scale science. A special supplement to *Nicotine and Tobacco Research* laid out in detail the vision for a transdisciplinary research strategy in tobacco control and how it was modeled, implemented, and evaluated.[107]

Other cancer outcomes await this depth of transdisciplinary scrutiny. Fruit and vegetable consumption may prevent cancer, but adherence to dietary guidelines for this consumption differs in the U.S. by race and SES.[64] A lack of exercise, poor diet, and obesity are associated with lower SES. A sedentary lifestyle is strongly related to lower income in every race and ethnic group and both genders.[108] Good evidence directly associates the lack of physical activity with cancers of the colorectum and prostate—and possibly breast cancer.[109] The Western diet staples of red meat and animal fat contribute to heart disease and cancer, especially colon cancer.[110] Overweight and obesity, also linked to certain cancers,[111] increased markedly in the U.S. for both children and adults between 1976 and 1980, and between 1988 and 1994,[112] and it seems clear that current diet and physical activity behaviors, as well as the practices of the food-marketing of industry in the U.S., promote obesity.[63,65,113] Differential uses of health services are key factors in outcomes related to these cancers, as discussed above.

Early-detection practices, a proven approach for secondary prevention for several cancer sites, are heavily dependent on the behaviors of individuals and providers. Screening and early detection, followed by timely treatment, increase survival for cervical, breast, colorectal, and possibly prostate cancers. Here again, the social context of healthcare access, quality, and price is critical, and the strongest predictors for the use of cancer screening are consistent health-insurance coverage and a consistent source of care.[114] Contractions in the economy and unemployment have been linked to a lessened likelihood that women, especially African-American women, will be diagnosed at an early stage of breast cancer, due to either less use of screening or less willingness to seek medical care for possible symptoms of cancer.[115] Understanding both the web of causation and a means to equalize access to cancer screening poses challenges for transdisciplinary science.[37]

Biological level. Finally, transdisciplinary cancer research should assist the understanding of how the social context influences biological pathways in cancer. Only a small percentage (estimated at less than 5%) of cancers are currently attributable to inherited genetic susceptibility.[116] However, common genetic polymorphisms and epigenetic characteristics interact with or are influenced by the social environment, making it clear that a better understanding is needed of how the social context affects cancer biology.[117,118] At least two pathways have been proposed: (1) psychological stress linked to down-regulation in the immune system[119–121] and (2) distress interfering with DNA repair and apoptosis,[122,123] but there are likely many others yet to be described. For example, the population health concept of *weathering*, proposed to explain premature morbidity among African-American women,[124] is consistent with biological findings[125] and provides an example of *embodiment*.[12]

Theories that seek to explain how social forces affect the overall disease burden and yield inequalities in health outcomes tend to focus on either material conditions or psychosocial mechanisms.[126] Proponents of material conditions hold that social factors, ranging from advertising to income distribution, have an indirect effect on cancer through behaviors such as tobacco use, dietary choices, Internet use, access to cancer-screening resources, and the ability to choose where to live and work. These social factors are reflected in the nonrandom distribution of cancer incidence. Proponents of the psychosocial theory focus on how adverse social conditions work directly through physiologic pathways in the endocrine or immunologic systems to cause stress and disease.[127,128] These two types of theories are not mutually exclusive, and need to be pursued and linked to increase the nascent understanding of how social determinants of cancer "get under the skin." As mentioned above, Glass and McAtee[99] have begun this effort by conceptualizing risk regulators that mediate upstream factors and associate them with the biological pathways leading to cancer outcomes. Science is only beginning to explore the causal links between biological mechanisms and social determinants or fundamental causes, and more needs to be done. Perhaps most clearly of all, this challenge lends itself to a transdisciplinary approach.

Implications for Cancer Prevention and Control

A framework has been presented here for a transdisciplinary science approach to cancer control that will reveal the causal links between biology and the social determinants of cancer. Identified were the main end-points available from cancer registries (i.e., incidence, survival, and mortality) and the value of examining social gradients in cancer outcomes. Multiple levels of analysis are needed to understand the diverse pathways and mechanisms behind these gradients and to determine how they are linked to the social environment; healthcare delivery; and behavioral, psychological, and biological levels in order to fashion more effective interventions. Interventions focused on changing individual behaviors in isolation have not proven adequate. Social policies to control tobacco use have been effective, and it may be time to consider other interventions at the social level, such as policies that will promote a sustainable economy, environmental justice, and the equalization of resource distribution, including healthcare access. Such an approach is consistent with national and international efforts aimed at modifying the social determinants of health.[129,130] The data available from current registry systems, surveys, and administrative records describe the range of biological, clinical, and social influences among different cancer sites. Especially when linked, they present rich opportunities for multilevel, transdisciplinary research all along the cancer continuum. Because of increased interest in population health, in transdisciplinary initiatives, and in eliminating health disparities, the time is ripe for transdisciplinary research and training.[8,131,132]

Substantial government and foundation support is now being directed toward these goals by the Robert Wood Johnson Foundation Health & Society Scholars Program,[133] the NIH Strategic Research Plan to Reduce and Ultimately Eliminate Health Disparities,[134] the 2009 Nation's Investment in Cancer Research Plan,[135] the Centers for Population Health and Health Disparities,[136] the Transdisciplinary Tobacco Use Research Centers,[137] NCI Centers of Excellence in Cancer Communication Research,[138] and the Transdisciplinary Research on Energetics and Cancer Centers.[139] It is hoped that readers will find this conceptual framework a useful beginning for taking advantage of these and other opportunities to further the development of transdisciplinary cancer control science.

The authors would like to thank Penny Randall-Levy, Scientific Consulting Group, for her expert assistance managing references.

No financial disclosures were reported by the authors of this paper.

References

1. Howe HL, Wu X, Ries LA, et al. Annual report to the nation on the status of cancer, 1975–2003, featuring cancer among U.S. Hispanic/Latino populations. Cancer 2006;107:1711–42.
2. Brown ML, Lipscomb J, Snyder C. The burden of illness of cancer: economic cost and quality of life. Annu Rev Public Health 2001;22:91–113.
3. Smedley BD, Syme SL, Committee on Capitalizing on Social Science and Behavioral Research to Improve the Public's Health. Promoting health:

intervention strategies from social and behavioral research. Am J Health Promot 2001;15:149–66. Comment in: Am J Health Promot 2001; 15:iii–v.
4. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
5. Nass SJ, Stillman B. Large-scale biomedical science: exploring strategies for future research. Washington DC: The National Academies Press, 2003.
6. Best A, Hiatt RA, Cameron R, Rimer BK, Abrams DB. The evolution of cancer control research: an international perspective from Canada and the U.S. Cancer Epidemiol Biomarkers Prev 2003;12:705–12.
7. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
8. Neuhauser L, Richardson D, Mackenzie S, Minkler M. Advancing transdisciplinary and translational research practice: issues and models of doctoral education in public health. J Res Pract 2007;3:M19.
9. Engineering Research Board, National Research Council. Bioengineering systems research in the U.S.: an overview. In: Directions in engineering research: an assessment of opportunities and needs. Washington DC: National Academy Press, 1987.
10. Bassingthwaighte JB, Quinn JA, Cooper RD. Bioengineering systems research in the U.S.: an overview report of the Engineering Research Board, National Research Council. Ann Biomed Eng 1989;17:301–7.
11. White RJ, Bassingthwaighte JB, Charles JB, Kushmerick MJ, Newman DJ. Issues of exploration: human health and wellbeing during a mission to Mars. 2003;31:7–16.
12. Krieger N. Embodying inequality: a review of concepts, measures, and methods for studying health consequences of discrimination. Int J Health Serv 1999;29:295–352.
13. McLeroy KR, Bibeau D, Steckler A, Glanz K. An ecological perspective on health promotion programs. Health Educ Q 1988;15:351–77.
14. Bronfenbrenner U. Toward an experimental ecology of human development. Am Psychol 1977;32:513–31.
15. Berkman LF, Kawachi I, eds. Social epidemiology. New York: Oxford University Press, 2000.
16. Krieger N. Epidemiology and the web of causation: has anyone seen the spider? Soc Sci Med 1994;39:887–903.
17. Phelan JC, Link BG, Diez-Roux A, Kawachi I, Levin B. "Fundamental causes" of social inequalities in mortality: a test of the theory. J Health Soc Behav 2004;45:265–85.
18. Krieger N. Proximal, distal, and the politics of causation: what's level got to do with it? Am J Public Health 2008;98:221–30.
19. National Cancer Institute, Division of Cancer Control and Population Sciences. Cancer control continuum. 2007. www.cancercontrol.cancer.gov/od/continuum.html.
20. Diez Roux AV. A glossary for multilevel analysis. J Epidemiol Community Health 2002;56:588–94.
21. Diez Roux AV. Estimating neighborhood health effects: the challenges of causal inference in a complex world. Soc Sci Med 2004;58:1953–60.
22. Barry J, Breen N. The importance of place of residence in predicting late-stage diagnosis of breast or cervical cancer. Health Place 2005;11: 15–29.
23. Hiatt RA, Rimer BK. A new strategy for cancer control research. Cancer Epidemiol Biomarkers Prev 1999;8:957–64.
24. Task Force on Community Preventive Services. Guide to community preventive services website. CDC. 2005. www.thecommunityguide.org/about/default.htm#cite.
25. Krieger N. Defining and investigating social disparities in cancer: critical issues. Cancer Causes Control 2005;16:5–14.
26. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006;33: 515–31.
27. Anderson NB, Armstead CA. Toward understanding the association of socioeconomic status and health: a new challenge for the biopsychosocial approach. Psychosom Med 1995;57:213–25.
28. Andersen RM. Revisiting the behavioral model and access to medical care: does it matter? J Health Soc Behav 1995;36:1–10.
29. Kaplan GA. Economic policy is health policy: findings from the study of income, socioeconomic status, and health. In: Auerbach JA, Krimgold BK, eds. Income, socioeconomic status, and health: exploring the relationships. Washington DC: National Policy Association, 2001.
30. Vineis P. Misuse of genetic data in environmental epidemiology. Ann N Y Acad Sci 2006;1076:163–7.
31. Link BG, Northridge ME, Phelan JC, Ganz ML. Social epidemiology and the fundamental cause concept: on the structuring of effective cancer screens by socioeconomic status. Milbank Q 1998;76:375.
32. Kaplan GA. People and places: contrasting perspectives on the association between social class and health. Int J Health Serv 1996;26:507–19.
33. McKinlay JB. A case for refocusing upstream: the political economy of illness. In: Jaco EG, ed. Patients, physicians, and illness: a sourcebook in behavioral science and health. 3rd ed. New York: Free Press, 1979.
34. Marmot MG. Improvement of social environment to improve health. Lancet 1998;351:57–60.
35. Evans RG, Barer ML, Marmot TR, eds. Why are some people healthy and others not? The determinants of health of populations. New York: Aldine De Gruyter, 1994.
36. Tomatis L. Inequalities in cancer risks. Semin Oncol 2001;28:207–9.
37. Pasick RJ, Hiatt RA, Paskett ED. Lessons learned from community-based cancer screening intervention research. Cancer 2004;101:1146–64.
38. Masi CM, Olopade OI. Racial and ethnic disparities in breast cancer: a multilevel perspective. Med Clin North Am 2005;89:753–70.
39. USDHHS. Healthy People 2010, 2nd ed. Vol. I, Part A. www.healthypeople.gov/publications/.
40. USDHHS. Healthy People 2010, 2nd ed. Vol II, Part B. www.healthypeople.gov/publications/.
41. IOM, Commission on Life Sciences, National Research Council. Ensuring quality cancer care. Hewitt M, Simone V, eds. Washington DC: National Academy Press, 1999.
42. President's Cancer Panel. Voices of a broken system: real people, real problems. President's Cancer Panel Report of the Chairman, 2000–2001. Bethesda MD: National Cancer Institute, 2001.
43. Ries LAG, Harkins D, Krapcho M, et al. SEER cancer statistics review, 1975–2003. Bethesda MD: National Cancer Institute, 2006. seer.cancer.gov/csr/1975_2003/.
44. American Cancer Society. Cancer facts & figures 2007. Atlanta GA: American Cancer Society, 2007.
45. Singh GK, Miller BA, Hankey BF, Edwards BK. Area socioeconomic variations in U.S. cancer incidence, mortality, stage, treatment, and survival, 1975–1999. Bethesda MD: National Cancer Institute, 2003.
46. Berry DA, Cronin KA, Plevritis SK, et al. Effect of screening and adjuvant therapy on mortality from breast cancer. N Engl J Med 2005;353:1784–92.
47. Miller BA, Kolonel LN, Bernstein L, et al. Racial/ethnic patterns of cancer in the U.S. 1988–1992. Bethesda MD: National Cancer Institute, 1996.
48. Devesa SS, Diamond EL. Association of breast cancer and cervical cancer incidences with income and education among whites and blacks. J Natl Cancer Inst 1980;65:515–28.
49. Singh GK. Area deprivation and widening inequalities in U.S. mortality, 1969–1998. Am J Public Health 2003;93:1137–43.
50. O'Campo P, Xue X, Wang MC, Caughy M. Neighborhood risk factors for low birthweight in Baltimore: a multilevel analysis. Am J Public Health 1997;87:1113–8.
51. Hiatt RA. The future of cancer surveillance. Cancer Causes Control 2006;17:639–46.
52. Singh GK, Siahpush M. All-cause and cause-specific mortality of immigrants and native born in the U.S. Am J Public Health 2001;91:392–9.
53. Smith GD, Neaton JD, Wentworth D, Stamler R, Stamler J. Socioeconomic differentials in mortality risk among men screened for the Multiple Risk Factor Intervention Trial: I. White men. Am J Public Health 1996;86: 486–96.
54. Marmot MG. Health inequalities among British civil servants in the Whitehall II Study. Lancet 1991;337:1387–93.
55. Adler NE, Boyce T, Chesney MA, et al. Socioeconomic status and health. The challenge of the gradient. Am Psychol 1994;49:15–24.
56. Krieger N. Analyzing socioeconomic and racial/ethnic patterns in health and health care. Am J Public Health 1993;83:1086–7.
57. Diez-Roux AV. Bringing context back into epidemiology: variables and fallacies in multilevel analysis. Am J Public Health 1998;88:216–22.
58. Diez-Roux AV. Multilevel analysis in public health research. Annu Rev Public Health 2000;21:171–92.
59. McKinlay JB, Potter DA, Feldman HA. Non-medical influences on medical decision-making. Soc Sci Med 1996;42:769–76.
60. Wilkinson RG. Unhealthy societies—the afflictions of inequality. London: Routledge, 1996.
61. Krieger N. Embodiment: a conceptual glossary for epidemiology. J Epidemiol Community Health 2005;59:350–5.
62. Fertilizing or contaminating? Environ Health Perspect 1999;107:A136–A137. Erratum in: Environ Health Perspect 1999;107:A293.

63. McNamara PE, Ranney CK, Kantor LS, Krebs-Smith SM. The gap between food intakes and the Pyramid recommendations: measurement and food system ramifications. Food Policy 1999;24:117–33.
64. Kumanyika SK, Krebs-Smith SM. Preventive nutrition issues in ethnic and socioeconomic groups in the U.S. In: Bendich A, Deckelbaum RJ, eds. Primary and secondary preventive nutrition. Totowa NJ: Humana Press Inc., 2000.
65. Schlosser E. Fast food nation: the dark side of the all-American meal. New York: Houghton Mifflin, 2001.
66. Pollan M. Unhappy meals. The New York Times Magazine. 2007 Jan 28:38–50.
67. Criss RE, Davisson ML. Fertilizers, water quality, and human health. Environ Health Perspect 2004;112:A536.
68. Daly HE. Economics in a full world. Sci Am 2005;293:100–7.
69. Hadorn GH, Bradley D, Pohl C, Rist S, Wiesmann U. Implications of transdisciplinarity for sustainability research. Ecol Econ 2006;60:119–28.
70. Ohl C, Krauze K, Grunbuhel C. Towards an understanding of long-term ecosystem dynamics by merging socio-economic and environmental research: criteria for long-term socio-ecological research sites selection. Ecol Econ 2007;63:383–91.
71. IOM. Toward environmental justice: research, education, and health policy needs. Washington DC: National Academy Press, 1999.
72. Bullard RD. Confronting environmental racism: voices from the grassroots. Cambridge MA: South End Press, 1993.
73. Jorgenson JL. Aldrin and dieldrin: a review of research on their production, environmental deposition and fate, bioaccumulation, toxicology, and epidemiology in the U.S. Environ Health Perspect 2001;109:113–39.
74. Maynard M. Conversation with Robert Bullard. Atlanta Magazine. March 2007:91, 130–1.
75. Norton BG, Noonan D. Ecology and valuation: big changes needed. Ecol Econ 2007;63:664–75.
76. Berrigan D, Troiano RP. The association between urban form and physical activity in U.S. adults. Am J Prev Med 2002;23:74–9.
77. Martinez ME, Giovannucci E, Spiegelman D, Hunter DJ, Willett WC, Colditz GA. Leisure-time physical activity, body size, and colon cancer in women. Nurses' Health Study Research Group. J Natl Cancer Inst 1997;89:948–55.
78. Levi F, Pasche C, Lucchini F, Tavani A, La Vecchia C. Occupational and leisure-time physical activity and the risk of colorectal cancer. Eur J Cancer Prev 1999;8:487–93.
79. LaVeist TA, Wallace JM Jr. Health risk and inequitable distribution of liquor stores in African American neighborhood. Soc Sci Med 2000; 51:613–7.
80. Inagami S, Cohen DA, Finch BK, Asch SM. You are where you shop: grocery store locations, weight, and neighborhoods. Am J Prev Med 2006;31:10–7.
81. Neighborhood safety and the prevalence of physical inactivity—selected states, 1996. MMWR Morb Mortal Wkly Rep 1999;48:143–6.
82. Williams DR, Collins C. Racial residential segregation: a fundamental cause of racial disparities in health. Public Health Rep 2001;116:404–16.
83. Evans RG. Strained mercy. Toronto ON: Butterworth, 1984.
84. Franks P, Clancy CM, Gold MR. Health insurance and mortality. Evidence from a national cohort. JAMA 1993;270:737–41.
85. Kaiser Family Foundation. Employer health benefits: 2005 summary of findings. Kaiser Family Foundation and Health Research and Educational Trust. 2005. www.kff.org/insurance/7315/sections/upload/7316.pdf.
86. Schiller JS, Barnes P. Early release of selected estimates based on data from the January–September 2006 National Health Interview Survey. National Center for Health Statistics, 2007. www.cdc.gov/nchs/data/nhis/earlyrelease/200703_01.pdf.
87. IOM. Access to health care in America. Millman M, ed. Washington DC: National Academy Press, 1993.
88. Weissman JS, Epstein AM. Falling through the safety net: insurance status and access to health care. Baltimore: The Johns Hopkins University Press, 1994.
89. Katz SJ, Hofer TP. Socioeconomic disparities in preventive care persist despite universal coverage. Breast and cervical cancer screening in Ontario and the U.S. JAMA 1994;272:530–4.
90. Katz SJ, Zemencuk JK, Hofer TP. Breast cancer screening in the U.S. and Canada, 1994: socioeconomic gradients persist. Am J Public Health 2000;90:799–803.
91. IOM. Crossing the quality chasm: a new health system for the 21st century. Washington DC: National Academy Press, 2001.
92. IOM. Unequal treatment: confronting racial and ethnic disparities in health care. In: Smedley BD, Stith AY, Nelson AR, eds. Washington DC: National Academy Press, 2002.
93. Shavers VL, Brown ML. Racial and ethnic disparities in the receipt of cancer treatment. J Natl Cancer Inst 2002;94:334–57.
94. Bach PB, Cramer LD, Warren JL, Begg CB. Racial differences in the treatment of early-stage lung cancer. N Engl J Med 1999;341:1198–205.
95. Polednak AP. Racial differences in the treatment of early-stage lung cancer. N Engl J Med 2000;342:517–8.
96. Ballard-Barbash R, Potosky AL, Harlan LC, Nayfield SG, Kessler LG. Factors associated with surgical and radiation therapy for early stage breast cancer in older women. J Natl Cancer Inst 1996;88:716–26.
97. Doll R, Peto R. The causes of cancer: quantitative estimates of avoidable risks of cancer in the U.S. today. J Natl Cancer Inst 1981;66:1197–308.
98. Abrams DB, Leslie F, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res 2003;5(1S):S5–S10.
99. Glass TA, McAtee MJ. Behavioral science at the crossroads in public health: extending horizons, envisioning the future. Soc Sci Med 2006; 62:1650–71.
100. Davis RM. Current trends in cigarette advertising and marketing. N Engl J Med 1987;316:725–32.
101. Fichtenberg CM, Glantz SA. Effect of smoke-free workplaces on smoking behaviour: systematic review. BMJ 2002;325:188.
102. Ong MK, Glantz SA. Free nicotine replacement therapy programs vs implementing smoke-free workplaces: a cost-effectiveness comparison. Am J Public Health 2005;95:969–75.
103. Frieden TR, Mostashari F, Kerker BD, Miller N, Hajat A, Frankel M. Adult tobacco use levels after intensive tobacco control measures: New York City, 2002–2003. Am J Public Health 2005;95:1016–23.
104. Stillman FA, Hartman AM, Graubard BI, Gilpin EA, Murray DM, Gibson JT. Evaluation of the American Stop Smoking Intervention Study (ASSIST): a report of outcomes. J Natl Cancer Inst 2003;95: 1681–91.
105. Baker TB, Hatsukami DK, Lerman C, O'Malley SS, Shields AE, Fiore MC. Transdisciplinary science applied to the evaluation of treatments for tobacco use. Nicotine Tob Res 2003;5(1S):S89–S99.
106. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
107. Swan GE, Balfour DJ, eds. Nicotine and tobacco research supplement: transdisciplinary tobacco use research centers. Nicotine Tob Res 2003; 5(1S):S1-S107.
108. Prevalence of sedentary lifestyle—Behavioral Risk Factor Surveillance System, U.S., 1991. MMWR Morb Mortal Wkly Rep 1993;42:576–9.
109. Monninkhof EM, Elias SG, Vlems FA, et al. Physical activity and breast cancer: a systematic review. Epidemiology 2007;18:137–57.
110. Larsson SC, Wolk A. Meat consumption and risk of colorectal cancer: a meta-analysis of prospective studies. Int J Cancer 2006;119:2657–64.
111. Calle EE, Teras LR, Thun MJ. Obesity and mortality. N Engl J Med 2005;353:2197–9.
112. Flegal KM, Troiano RP. Changes in the distribution of body mass index of adults and children in the U.S. population. Int J Obes Relat Metab Disord 2000;24:807–18.
113. Troiano RP, Briefel RR, Carroll MD, Bialostosky K. Energy and fat intakes of children and adolescents in the U.S.: data from the national health and nutrition examination surveys. Am J Clin Nutr 2000;72(5S):1343S–53S.
114. Breen N, Wagener DK, Brown ML, Davis WW, Ballard-Barbash R. Progress in cancer screening over a decade: results of cancer screening from the 1987, 1992, and 1998 National Health Interview Surveys. J Natl Cancer Inst 2001;93:1704–13.
115. Catalano RA, Satariano WA, Ciemins EL. Unemployment and the detection of early stage breast tumors among African Americans and non-Hispanic whites. Ann Epidemiol 2003;13:8–15.
116. Trichopoulos D, Li FP, Hunter DJ. What causes cancer? Sci Am 1996;275:80–7.
117. Ryff CD, Singer BH. Social environments and the genetics of aging: advancing knowledge of protective health mechanisms. J Gerontol B Psychol Sci Soc Sci 2005;60 Spec No 1:12–23.
118. Dalton SO, Boesen EH, Ross L, Schapiro IR, Johansen C. Mind and cancer: do psychological factors cause cancer? Eur J Cancer 2002;38:1313–23.
119. Ellison GL, Coker AL, Hebert JR, Sanderson SM, Royal CD, Weinrich SP. Psychosocial stress and prostate cancer: a theoretical model. Ethn Dis 2001;11:484–95.
120. Antoni MH, Lutgendorf SK, Cole SW, et al. The influence of biobehavioural factors on tumour biology: pathways and mechanisms. Nat Rev Cancer 2006;6:240–8.

121. Kiecolt-Glaser JK, McGuire L, Robles TF, Glaser R. Emotions, morbidity, and mortality: new perspectives from psychoneuroimmunology. Annu Rev Psychol 2002;53:83–107.
122. Kiecolt-Glaser JK, Glaser R. Psychoneuroimmunology and cancer: fact or fiction? Eur J Cancer 1999;35:1603–7.
123. Bovbjerg DH, Kim YT, Schwab R, Schmitt K, DeBlasio T, Weksler ME. "Cross-wiring" of the immune response in old mice: increased autoantibody response despite reduced antibody response to nominal antigen. Cell Immunol 1991;135:519–25.
124. Geronimus AT. Understanding and eliminating racial inequalities in women's health in the U.S.: the role of the weathering conceptual framework. J Am Med Womens Assoc 2001;56:133–50.
125. McEwen BS. Sex, stress and the hippocampus: allostasis, allostatic load and the aging process. Neurobiol Aging 2002;23:921–39.
126. Kawachi I, Subramanian SV, Almeida-Filho N. A glossary for health inequalities. J Epidemiol Community Health 2002;56:647–52.
127. McEwen BS, Seeman T. Protective and damaging effects of mediators of stress. Elaborating and testing the concepts of allostasis and allostatic load. Ann N Y Acad Sci 1999;896:30–47.
128. McDonald PG, Antoni MH, Lutgendorf SK, et al. A biobehavioral perspective of tumor biology. Discov Med 2005;5:520–6.
129. Acheson D. Independent inquiry into inequalities in health. London: The Stationery Office, 1998.
130. Marmot M. Social determinants of health inequalities. Lancet 2005; 365:1099–104.
131. House JS, Williams DR. Understanding and reducing socioeconomic and racial/ethnic disparities in health. In: Smedley BD, Syme SL, eds. Promoting health: intervention strategies from social and behavioral research. Washington DC: National Academy Press, 2000.
132. Lynch J, Kaplan G. Socioeconomic position. In: Berkman LS, Kawachi I, eds. Social epidemiology. New York: Oxford University Press, 2000.
133. The Robert Wood Johnson Foundation. The Robert Wood Johnson Health & Society Scholars Program. 2007. www.healthandsocietyscholars.org/about/.
134. NIH. NIH strategic research plan to reduce and ultimately eliminate health disparities. NIH, 2007. ncmhd.nih.gov/our_programs/strategic/pubs/VolumeI_031003EDrev.pdf.
135. National Cancer Institute. The 2009 nation's investment in cancer research plan. Bethesda MD: National Cancer Institute, 2007. plan.cancer.gov.
136. National Cancer Institute. Centers for Population Health and Health Disparities. 2007. cancercontrol.cancer.gov/populationhealthcenters/.
137. National Cancer Institute. Transdisciplinary tobacco use research centers (TTURCS). 2007. cancercontrol.cancer.gov/tcrb/research_topic-transdisciplinary.html.
138. National Cancer Institute. NCI centers of excellence in cancer communication research. 2007. cancercontrol.cancer.gov/hcirb/ceccr/.
139. National Cancer Institute. Transdisciplinary research on energetics and cancer (TREC) Centers. 2007. cancercontrol.cancer.gov/trec/.

Methodologic Contributions

Measuring Collaboration and Transdisciplinary Integration in Team Science

Louise C. Mâsse, PhD, Richard P. Moser, PhD, Daniel Stokols, PhD, Brandie K. Taylor, MA, Stephen E. Marcus, PhD, Glen D. Morgan, PhD, Kara L. Hall, PhD, Robert T. Croyle, PhD, William M. Trochim, PhD

Purpose: As the science of team science evolves, the development of measures that assess important processes related to working in transdisciplinary teams is critical. Therefore, the purpose of this paper is to present the psychometric properties of scales measuring collaborative processes and transdisciplinary integration.

Methods: Two hundred-sixteen researchers and research staff participating in the Transdisciplinary Tobacco Use Research Centers (TTURC) Initiative completed the TTURC researcher survey. Confirmatory-factor analyses were used to verify the hypothesized factor structures. Descriptive data pertinent to these scales and their associations with other constructs were included to further examine the properties of the scales.

Results: Overall, the hypothesized-factor structures, with some minor modifications, were validated. A total of four scales were developed, three to assess collaborative processes (satisfaction with the collaboration, impact of collaboration, trust and respect) and one to assess transdisciplinary integration. All scales were found to have adequate internal consistency (i.e., Cronbach α's were all >0.70); were correlated with intermediate markers of collaborations (e.g., the collaboration and transdisciplinary-integration scales were positively associated with the perception of a center's making good progress in creating new methods, new science and models, and new interventions); and showed some ability to detect group differences.

Conclusions: This paper provides valid tools that can be utilized to examine the underlying processes of team science—an important step toward advancing the science of team science.
(Am J Prev Med 2008;35(2S):S151–S160)

Background

Several studies[1–4] have documented that, since the mid-1950s, the natural, behavioral, and social sciences have made a pronounced shift from individually oriented research toward team-based scientific initiatives. This trend toward greater teamwork in science is paralleled by a growing emphasis on cross-disciplinary approaches to research and training.[5–7] Substantial investments by government agencies and private foundations in cross-disciplinary centers and teams have triggered a lively debate about the relative merits of individual-versus-team–based models of research and the emergence of a new area of program evaluation research, namely, the science of team science.[8–11] Evaluations of team science initiatives aim to identify, measure, and understand the processes and outcomes of large-scale research collaborations. Given the substantial amount of federal and private resources that have been allocated to establish and maintain team science initiatives, it is essential that concerted efforts be made to evaluate both their near-, mid-, and longer-term collaborative processes and outcomes.[12–14]

The science-of-team-science field is at a relative early stage in its development and can benefit from the development of psychometrically valid and reliable measures of collaborative processes, especially those involving cross-disciplinary synergy and integration. As these initial collaborative processes may be integrally linked to the achievement of subsequent and far-reaching benefits to science and society, it is important to develop reliable and valid measures of these con-

From the Centre for Community Child Health Research, University of British Columbia (Mâsse), Vancouver, British Columbia, Canada; the Division of Cancer Control and Population Sciences (Moser, Marcus, Morgan, Hall, Croyle), National Cancer Institute, and the Office of Portfolio Analysis and Strategic Initiatives (Taylor), NIH, Bethesda, Maryland; the School of Social Ecology, University of California Irvine (Stokols), Irvine, California; and the Department of Policy Analysis and Management, Cornell University (Trochim), Ithaca, New York

Address correspondence and reprint requests to: Louise C. Mâsse, PhD, University of British Columbia, Department of Pediatrics, Centre for Community Child Health Research, L408, 4480 Oak Street, Vancouver, British Columbia V6H 3V4, Canada. E-mail: lmasse@cw.bc.ca.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.020

structs early-on as a basis for evaluating their influence on the cumulative contributions of a team initiative over a longer period.

Findings are presented here from an early-stage evaluation of the National Cancer Institute's (NCI) Transdisciplinary Tobacco Use Research Centers (TTURC) initiative.[15] The overall goals of the study were (1) to create and validate new methods and metrics for assessing cross-disciplinary collaboration and transdisciplinary integration within the context of the TTURC initiative, and (2) to develop and preliminarily assess a conceptual logic model linking the sequential phases, processes, and outcomes associated with large team science initiatives more generally. The TTURC program[15] is one of four large-scale, cross-disciplinary initiatives organized and funded since 1999 by the Division of Cancer Control and Population Sciences within NCI.[a] Currently, the total NIH investment into those four initiatives (TTURC, the Centers of Excellence in Cancer Communications Research, the Centers for Population Health and Health Disparities, and the Transdisciplinary Research on Energetics and Cancer centers) that address both basic and applied research in cancer control is approximately $286 million.[15–18,b]

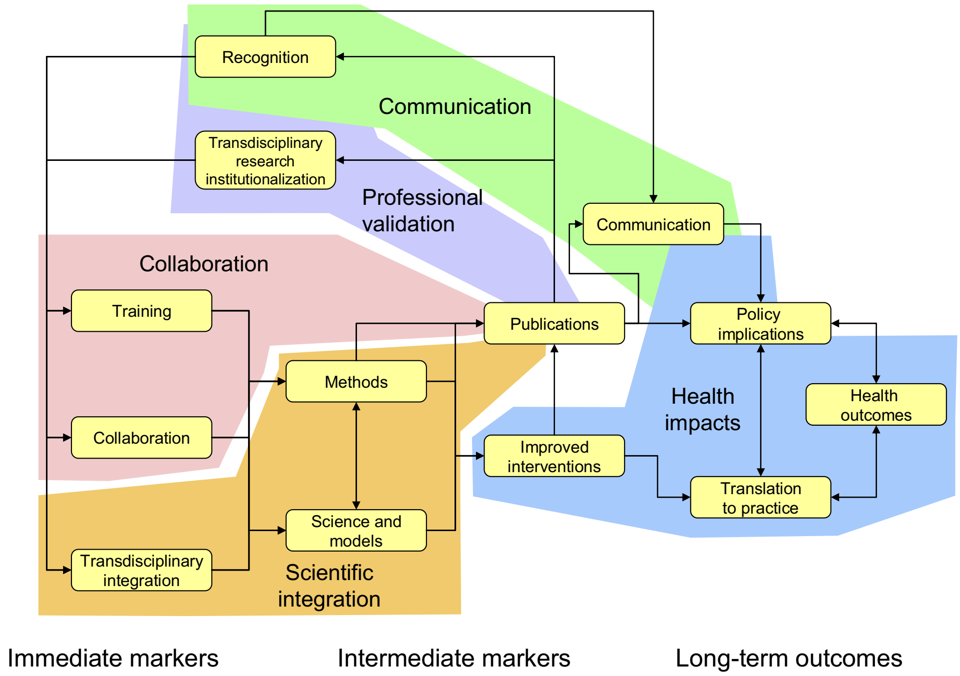


Figure 1. Logic model for the TTURC evaluation that guided the development of the researcher-survey items showing inter-relationships among constructs divided into expected temporal-outcome groups

Conceptual Foundations of the TTURC Initiative Evaluation Study

The TTURC initiative is rooted in Rosenfield's conceptualization of transdisciplinary scientific collaboration.[19,20] Rosenfield describes a continuum of collaborative research ranging from unidisciplinary and multidisciplinary to interdisciplinary and transdisciplinary approaches. According to Rosenfield, transdisciplinary collaborations (compared to multidisciplinary and interdisciplinary forms of cross-disciplinary research) lead to the development of shared conceptual frameworks that not only integrate but also transcend the individual disciplinary perspectives represented by various members of the research team. These transdisciplinary conceptual frameworks, integrating the concepts and methods drawn from multiple disciplines and analytic levels, have the greatest potential to generate truly novel scientific and societal advances—reflected, for example, in a more comprehensive understanding of nicotine-addiction processes, the development of more-powerful smoking prevention strategies, and a substantial reduction of tobacco-related disease and mortality in the population.[21,22]

As a basis for understanding the conceptual and empirical links among cross-disciplinary collaboration, transdisciplinary integration, and the more distal scientific achievements and health outcomes generated by the TTURC initiative, Trochim and colleagues[23] developed a comprehensive logic model to evaluate large initiatives (ELI). TTURC investigators, funders, and other stakeholders (staff and scientific consultants) first completed a web-based concept-mapping exercise for the purpose of deriving key constructs associated with effective transdisciplinary-team initiatives and understanding the temporal relationships among the different constructs. They later developed a researcher survey that was designed to assess key components of the ELI logic model. The logic model (Figure 1) incorporates five general clusters: collaboration, communication, professional validation, scientific integration, and

[a]The first 5-year phase of the TTURC initiative was a $70-million program funded by NCI and the National Institute of Drug Abuse (NIDA); it supported seven research centers between 1999 and 2004. The Robert Wood Johnson Foundation committed an additional $14 million over 5 years to complement NCI's and NIDA's commitment. The TTURC initiative was renewed by NIH in 2004 and is currently in its second 5-year funding cycle.

[b]The $286-million figure is expected to rise substantially as the various initiatives move into their second 5-year funding cycles.

health impacts. The collaboration cluster subsumes the dimensions of training, collaboration, and transdisciplinary integration. These constructs serve as proximal, or early-stage, markers of team effectiveness during the initial phase of the TTURC initiative. To the extent that the TTURCs are effective over the course of their initial and later phases, the levels of intellectual collaboration and transdisciplinary integration will be higher at the outset, thereby prompting changes in investigators' methods and models. Those methodologic and conceptual changes, in turn, enable translations of transdisciplinary knowledge into new health promotion interventions, policy innovations, and improved health outcomes. This hypothesized sequence of changes is ultimately expected to facilitate greater recognition of the value of transdisciplinary science and the broad-based adoption or institutionalization of transdisciplinary approaches to tobacco-use research.[23] Operationalizing the constructs included in the ELI logic model is an important starting point for evaluating the potential benefits of transdisciplinary research and is the focus of this paper.

The findings reported below focus on two major components of the ELI logic model, namely, the collaboration and transdisciplinary-integration constructs. Although the effectiveness of collaborative teams has been studied extensively in nonscientific venues, the measures employed in those contexts often do not generalize readily to scientific settings.[24–26] Therefore, some major purposes of this paper are to examine the factorial validity and internal consistency of three collaboration scales and one transdisciplinary-integration scale that were developed in the context of the TTURC initiative as well as to evaluate their associations with other constructs included in the ELI logic model (Figure 1).

Methods

Participants

Participants consisted of all TTURC investigators (principal investigators, co-investigators, project directors, research associates, and scientists); research staff; and trainees who were identified by each center's principal investigator as eligible respondents for the researcher survey. As part of the TTURC evaluation, each principal investigator completed a center survey, which provided a quick profile of the center and the number of staff who would be eligible to complete the researcher survey. Among the seven TTURCs, there were 234 eligible respondents (N=234); 216 completed the researcher survey, for an overall 92% response rate.

Data-Collection Protocol

The data were collected in the context of a program evaluation during the third year of the initiative. The TTURC principal investigators were primarily responsible for identifying someone who would serve as the point of contact for distributing the survey and reminding eligible respondents to complete it. The researchers and research staff were asked to complete the survey and mail it back in a self-addressed pre-paid envelope to the data processing center. To increase compliance, the data processing center compiled on a weekly basis the total number of Researcher Surveys received by each Center. The contact person received an anonymized update on their center's response rates, as well as response rates of the other centers (anonymized as well). The contact person was asked to send reminders to their colleagues and research staff to ensure an adequate response rate to the survey. At all times, the contact person or anyone involved were never aware of who responded to the Researcher Survey. Although the PIs, researchers, and research staff were encouraged to fill out the survey, their participation was completely voluntary.

TTURC Researcher Survey Development

The TTURC Researcher Survey is a 12-page instrument that included indices and scales that represented all the dimensions assessed by the ELI logic model (Figure 1). Concept mapping served as the basis for the ELI logic model, and also served to provide much of the initial content for developing the researcher survey. Additionally, because the concept-mapping process consisted of clustering statements into dimensions, the statements within these clusters formed the initial theoretical operationalization of the dimensions. The researcher-survey development was led by a methodology team (WTM, LCM, and SM co-authors) and was developed in collaboration with TTURC funders, TTURC researchers, and input from a consulting committee. The researcher survey went through several expert reviews and revisions, and received final approval from a consulting committee for administration to the TTURCs. Of particular interest to this paper are the sections that focused on collaboration and transdisciplinary research (see Appendixes A and B for a description of the items).

Collaboration

The researcher survey included 23 items that assessed collaboration. All items used a 5-point, Likert-type response format. Fifteen items used the stem *Please evaluate the collaboration within your center* with the following response anchors: *inadequate, poor, satisfactory, good,* and *excellent.* The other eight items started with *Please rate your views about collaboration with respect to your center-related research* with the response anchors *strongly disagree, somewhat disagree, not sure, somewhat agree,* and *strongly agree.* It was determined a priori that the factor structure of the collaboration scale would have three correlated factors. One factor was designed to assess *satisfaction with collaboration* using eight items: *acceptance of ideas, communication, researchers' strengths, organization, resolution of conflict, working styles, outside involvement,* and *discipline involvement.* A second factor, designed to assess the impact of collaboration, used 6 items: *meeting productivity, products productivity, overall productivity, research productivity, quality of research,* and *time burden.* A final factor, designed to assess trust and respect in the collaborative context, used four items: *being comfortable in showing limits, trusting colleagues, being open to criticism,* and *respect*). Five of the initial collaboration items were excluded from the analyses as they did not measure the above constructs.

Table 1. Model fit of the confirmatory-factor analysis, testing whether the hypothesized three-factor structure fit the collaboration items (n=144)

Model	Chi-square (df), p-value	RMSEA (90% CI)	SRMR	CFI/NNFI	CAIC	Residuals
Model 1	282.07 (132), <0.05	0.09 (0.07, 0.10)	0.06	0.97/0.94	352.20	−3.22 to 6.48 Some skewness
Model 2	255.01 (116), <0.05	0.09 (0.07, 0.10)	0.06	0.97/0.95	315.11	−3.22 to 6.48 Some skewness
Model 3	181.30 (114), <0.05	0.07 (0.05, 0.08)	0.05	0.99/0.96	260.82	−2.75 to 2.93 Normal

Model Comparisons	Chi-square difference	df	p-value	CAIC difference
Model 1 vs Model 2	27.06	16	>0.05	37.09
Model 2 vs Model 3	73.98	2	>0.05	54.29

Note: Model 1: Hypothesized three-factor structure; Model 2: hypothesized three-factor solution minus the item that assesses "time burden"; Model 3: Model 2 plus two correlated-error terms (one between Items 7 and 8, and a second between Items 12 and 13)
CAIC, corrected Aikaike's information criterion; CFI, comparative fit index; NNFI, non-normed fit index; RMSEA, root mean square residuals; SRMR, standardized root mean square residuals

Transdisciplinary Integration

The researcher survey had 15 items that measured attitudes about transdisciplinary research. Respondents were asked to indicate their attitudes about transdisciplinary research and to provide interpretations based on their understanding or perception of transdisciplinary research. All items used a 5-point, Likert-type format with the response options *strongly agree, somewhat disagree, not sure, somewhat agree,* and *strongly disagree.* It was determined a priori that the items likely measured one factor that assessed transdisciplinary integration.

ELI Intermediate Markers of Progress Toward Collaboration and Transdisciplinary Integration

Although the researcher survey included a number of indexes that corresponded to the ELI logic model (Figure 1), only four of the indexes (methods, science and models, improved interventions, and publications) were used here. These were seen as intermediate markers of progress within the centers. It should be noted that for these constructs, index measures were created. Overall, these indexes measured how much progress had been achieved by the TTURCs in these areas. The methods index was computed by averaging 7 items (e.g., development or refinement of methods for gathering data); 17 items were averaged for the sciences-and-models index (e.g., understanding multiple determinants of the stages of nicotine addiction); 12 items were averaged to measure improved interventions (e.g., progress in pharmacologic interventions); and, finally, the publications index was the sum of submitted and published articles and abstracts.

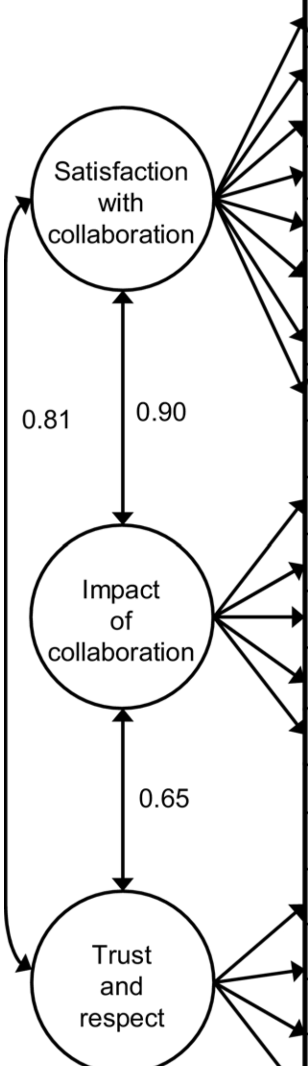
Data Analysis

Factor structure. All negatively worded items were reverse-coded for the analyses. Confirmatory-factor analyses, using the LISREL 8.8 software, served to validate the a priori-factor structure of the collaboration and transdisciplinary-integration scales. Parameter estimates were obtained using the maximum-likelihood method of estimation. As there are no agreed-upon standards for determining model fit, the criteria established by Hu and Bentler[27] for evaluating fit were followed. The chi-square goodness-of-fit test served to determine the overall fit of the factor structure, with a p-value <0.15 indicating that the residuals were no longer significant—hence, a good fit. Given that the chi-square is highly affected by sample size and the distributional properties of the items, other fit indexes were evaluated. Steiger's root mean square root error of approximation (RMSEA) was evaluated, with a value of 0.05 and an upper CI <0.08 indicating a good fit. The standardized root mean square residuals (SRMR) was evaluated, and a value of 0.05 represented a good fit. Both the comparative fit index (CFI) and the non-normed fit index (NNFI) were evaluated. These indexes compare the fit of the model to a baseline model with values bounded between 0 and 1. For both the CFI and NNFI, a value >0.95 is indicative of a good fit. Finally, the distribution of the standardized residuals was evaluated to assess overall model fit, where normally distributed standardized residuals ranging from −3.0 to 3.0 indicate a good fit. Any posthoc model modifications consisted of evaluating the modification indexes and determining whether the suggested change was theoretically defensible. If the revised model was nested within the original structure, a chi-square test of differences was computed to determine if the new model significantly improved the fit of the data.

Finally, the corrected Akaike's information criteria (CAIC) served to compare the fit of different models while accounting for the number of parameters estimated in the model; a lower CAIC was indicative of a better fit. Standardized factor loadings ranged from −1.00 to 1.00, and a value of <0.30 was used to assess items that loaded poorly on the hypothesized factor.

Relationship with ELI outcomes. It was hypothesized that the collaboration and the transdisciplinary-integration scales would be significantly correlated with select intermediate markers on the ELI logic model (methods, science and models, improved interventions, and publications). To assess these bivariate relationships, the potential clustering effect of the center was accounted for by first regressing each scale on the center (coded as a set of dummy variables) and then computing a Pearson product moment correlation between the resulting residuals.

Group differences. Finally, one-way ANOVAs were computed for each scale to examine if differences existed on these scales by respondent's role and by center, using the general linear model procedure in SAS to take into account the nested structure of the data. Posthoc analyses were conducted (as appropriate) using the least-significant-differences method. Although some differences were expected, these analyses were mainly exploratory. All analyses used a p-value <0.05 to determine significance.



Standardized paths (nonstandardized paths ± SD)	Items	Mean ± SD
0.71 (0.56 ± 0.06)	1. Acceptance of ideas	4.25 ± 0.85
0.83 (0.71 ± 0.06)	2. Communication	4.01 ± 0.91
0.85 (0.76 ± 0.06)	3. Strengths	4.23 ± 0.88
0.77 (0.67 ± 0.06)	4. Organization	3.91 ± 0.89
0.84 (0.77 ± 0.06)	5. Resolution of conflicts	3.82 ± 0.93
0.81 0.69 ± 0.06)	6. Working styles	3.99 ± 0.88
0.53 (0.46 ± 0.07)	7. Outside involvement	3.99 ± 0.90
0.63 (0.49 ± 0.06)	8. Discipline involvement	4.14 ± 0.82
Cronbach alpha = 0.91	**Subtotal**	**4.05** ± 0.71
0.75 (0.63 ± 0.06)	9. Meeting productivity	3.86 ± 0.87
0.72 (0.61 ± 0.06)	10. Products productivity	3.71 ± 0.87
0.88 (0.71 ± 0.06)	11. Overall productivity	4.01 ± 0.86
0.67 (0.76 ± 0.08)	12. Research productivity	4.03 ± 1.02
0.62 (0.56 ± 0.07)	13. Quality of research	4.29 ± 0.87
—	14. Time burden	3.18 ± 1.36
Cronbach alpha = 0.87	**Subtotal**	**4.00** ± 0.73
0.42 (0.29 ± 0.06)	14. Showing limits	4.47 ± 0.69
0.74 (0.55 ± 0.06)	15. Trust colleagues	4.47 ± 0.82
0.84 (0.82 ± 0.07)	16. Open to criticism	4.02 ± 1.03
0.71 (0.37 ± 0.04)	17. Respect	4.70 ± 0.59
Cronbach alpha = 0.75	**Subtotal**	4.41 ± 0.60

Error terms between items 7 and 8 (0.36) as well as items 12 and 13 (0.25) are correlated.

Figure 2. Factor structure of the collaboration scales

Internal consistency. The SPSS reliability subroutine was used to compute internal consistency (Cronbach's coefficient α) for the collaboration and transdisciplinary-integration scales. Using the lower-bound criteria for internal consistency, a Cronbach's α of at least 0.70 was considered adequate.[28]

Results

Demographic Information

Of the valid responses (n=202), 50% of the respondents (n=101) indicated that they had been with their center for ≥2 years, and 66.3% reported having worked <40 hours per week on TTURC-related efforts. The largest percentage of respondents (n=100) characterized their research role in the Center as investigator (49.3%), while others indicated their role as professional staff (25.1%); student (16.3%); and other (9.4%).

Respondents were asked to report their primary, secondary, and tertiary disciplinary affiliations. The most commonly reported disciplinary affiliations were psychology (n=88); public health (n=50); and behavioral medicine (n=44). Respondents also reported considerable collaboration with new disciplines in association with their TTURC-related efforts. While 76.9% (n=166) of the respondents had collaborated with at least one new discipline over the past year, 62.5% (n=135) reported collaborating with two or more new disciplines. The most-frequently mentioned new disciplines with which researchers reported collaborating included genetics (27.3%); public health (26.9%); communications (24.5%); epidemiology (22.7%); and biostatistics (20.8%), reflecting a broad spectrum of disciplines from the biological sciences to population health.

Factorial Validity of the Collaboration Scales

The confirmatory-factor analysis results for the collaboration scales are summarized in Table 1. The results showed that the a priori three-factor structure did not fit the data very well (the RMSEA, SRMR, and residuals were high). The results suggested that Item 14, *time burden (collaboration has posed a significant time burden in your research)*, did not load on the factor that assessed the impact of collaboration. Of the 18 items, this was the only item that was negatively worded. Given that the

Table 2. Model fit of the confirmatory-factor analysis, testing whether the hypothesized one-factor structure fit the transdisciplinary items (n=172)

Model	Chi-square (df), p-value	RMSEA (90% CI)	SRMR	CFI/NNFI	CAIC	Residuals
Model 1	222.67 (90), <0.05	0.10 (0.08, 0.11)	0.07	0.96/0.93	294.42	−3.13 to 6.11 Skewed
Model 2	182.61 (89), <0.05	0.08 (0.07, 0.10)	0.07	0.97/0.94	378.59	−2.87 to 4.57 Some skewness
Model 3	137.76 (86), <0.05	0.06 (0.04, 0.08)	0.05	0.98/0.98	346.77	−2.74 to 3.09 Normal

Model comparisons	Chi-square difference	df	p-value	CAIC difference
Model 1 vs Model 2	40.06	1	>0.05	84.17
Model 2 vs Model 3	44.85	3	>0.05	31.82

Note: Model 1: Hypothesized three-factor structure; Model 2: hypothesized three-factor solution minus the item that assesses "time burden"; Model 3: Model 2 plus two correlated-error terms (one between Items 7 and 8, and a second between Items 12 and 13)
CAIC, corrected Aikaike's information criterion; CFI, comparative fit index; NNFI, non-normed fit index; RMSEA, root mean square residuals; SRMR, standardized root mean square residuals

factor loading was extremely low (0.01), the solution was run without this item (Model 2). As shown in Table 1, the fit of Model 2 significantly improved compared to Model 1, but the solution remained inadequate (the RMSEA, SRMR, and residuals were high). Examination of the modification indexes revealed a weakness in the factor structure, suggesting the addition of two correlated-error terms to Model 2. A correlation between Items 7, *outside involvement*, and Item 8, *discipline involvement*, was added, as well as a correlation between Item 12, *research productivity*, and Item 13, *quality of research*.

It should be noted that adding these correlations suggests that the solution does not account for all of the correlations that exist among these four items. To address this issue, Model 3 added these two extra correlations (Table 1), which resulted in an adequate fit as well as a significant improvement in the fit of the model. The final three-factor solution is presented in Figure 2. The factor loadings (standardized paths) ranged from 0.42 on Item 15, *showing limits*, to a high of 0.88 on Item 11, *overall productivity*. Correlations among the factors were moderately high (the correlation between *impact of collaboration* and *trust and respect* was 0.65) to high (the correlation between *satisfaction with collaboration* and *impact of collaboration* was 0.90, and between *satisfaction with collaboration* and *trust and respect* was 0.81). Cronbach's α for each scale was adequate: 0.91 for *satisfaction with collaboration,* 0.87 for *impact of collaboration*, and 0.75 for *trust and respect*. Item and subscale means were high; on the 1- to 5-point Likert scale, the means were (in general) closer to the 4-point—indicative of overall satisfaction with the collaborative process. Overall item means and scale means were high, indicating satisfaction in these areas.

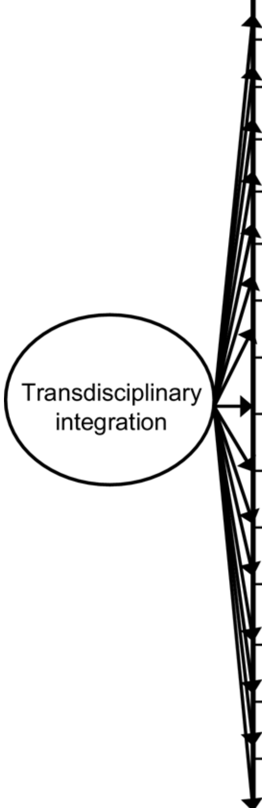
Factorial Validity of the Transdisciplinary-Integration Scale

The confirmatory-factor–analysis results of the transdisciplinary-integration scale are summarized in Table 2. The results showed that the hypothesized one-factor structure for the transdisciplinary items did not fit very well (inadequate RMSEA, SRMR, and standardized residuals). Examination of the modification indexes suggested that the correlation between two items (Item 6, *changes my research ideas*, and Item 7, *improved my research*) was not well-explained by the solution. Given that the content of these two items was related, a correlated-error term was added to the model (Model 2). Adding this correlated-error term significantly improved the fit of the model, but the solution remained inadequate (high RMSEA, SRMR, and standardized residuals). Re-examination of the modification indexes revealed that the correlations among all the negatively worded items (Items 2, 3, and 4) remained high.

Table 3. Pearson product moment correlations among the collaboration and transdisciplinary-integration scales with intermediate markers and long-term outcomes

	Methods (n=179)[a]	Science and models (n=183)[a]	Improved interventions (n=164)[a]	Publications (n=128)[a]
Satisfaction with collaboration	0.37**	0.48**	0.25**	0.18
Impact of collaboration	0.44**	0.52**	0.37**	0.10
Trust and respect	0.33**	0.40**	0.18*	0.04
Transdisciplinary integration	0.42**	0.38**	0.34**	0.03

[a]Note that the sample size varied slightly due to missing data.
*p<0.05; **p<0.001



Standardized paths (nonstandardized paths ± SD)	Items	Mean ± SD
0.72 (0.50 ± 0.05)	1. Values collaboration	4.50 ± 0.70
0.25 (0.27 ± 0.08)	2. Knowledge interference	4.07 ± 1.06
0.32 (0.35 ± 0.08)	3. Less productive	3.65 ± 1.06
0.21 (0.23 ± 0.08)	4. Fewer publications	2.45 ± 1.08
0.66 (0.53 ± 0.06)	5. Stimulates thinking	4.28 ± 0.78
0.60 (0.62 ± 0.07)	6. Changes research idea	3.74 ± 1.05
0.63 (0.63 ± 0.07)	7. Improved my research	3.81 ± 1.01
0.82 (0.69 ± 0.05)	8. Valuable science	4.41 ± 0.83
0.69 (0.63 ± 0.06)	9. Improves interventions	4.13 ± 0.90
0.73 (0.62 ± 0.06)	10. Discipline contribution	4.26 ± 0.83
0.67 (0.63 ± 0.07)	11. Sustained collaboration	3.92 ± 0.93
0.84 (0.70 ± 0.05)	12. Outweighs inconveniences	4.31 ± 0.82
0.82 (0.58 ± 0.04)	13. Comfortable environment	4.51 ± 0.73
0.67 (0.54 ± 0.06)	14. Effort to engage	4.33 ± 0.81
0.52 (0.42 ± 0.06)	15. Open-minded perspective	4.27 ± 0.81
Cronbach alpha = 0.89	**Subtotal**	4.05 ± 0.55

Error terms between items 6 and 7 (0.29) as well as items 2 and 3 (0.32), 2 and 4 (0.25), and 3 and 4 (0.30) are correlated.

Figure 3. Factor structure of the transdisciplinary-integration scales

To remedy this, a new model was fitted that included extra correlated-errors terms among all negatively worded items (Model 3), and resulted in an adequate fit and significant improvement in the fit of the model. As shown in the final solution (Figure 3), the factor loadings (standardized paths) for the negatively worded items (Item 2, *knowledge interference*; Item 3, *less productive*; and Item 4, *fewer publications*) were borderline adequate (>0.30) to inadequate (<0.30), indicating that although the overall fit of the model was improved by the addition of a correlated-error term among these items, these items remained poor indicators of transdisciplinary integration.

Associations with ELI Outcomes

Table 3 summarizes the associations for the collaboration and transdisciplinary-integration scales with select intermediate ELI outcomes. The results showed that the three scales for collaboration and the transdisciplinary-integration were significantly correlated with the following ELI outcomes: methods, science and models, and interventions.

Group Differences

Table 4 presents collaboration and transdisciplinary-integration scales by respondent's role and by center. The analyses revealed significant between-group differences by respondent's role for the trust-and-respect collaboration scale only ($F=3.47$ [$df=3, 183$], $p<0.05$) and revealed no significant differences for the other collaboration scales and the transdisciplinary-integration scale by respondent's role. Posthoc comparisons revealed that on the trust-and-respect factor, investigators' scores were significantly higher than those of "other" research staff ($p<0.05$), and students' scores were significantly higher than the scores of both the professional support staff scores ($p<0.05$) and the "other" research staff ($p<0.05$).

Finally, the results comparing differences by center revealed significant between-center differences for all the collaboration factors: *satisfaction with collaboration* ($F=9.42$ [$df=6, 171$], $p<0.05$); *impact on collaboration* ($F=7.87$ [$df=6, 170$]; $p<0.05$); *trust and respect* ($F=3.37$ [$df=6, 191$], $p<0.05$); the collaboration total score ($F=8.75$ [$df=6,174$], $p<0.05$); and the transdisciplinary-integration scale ($F=2.87$ [$df=6, 198$], $p<0.05$). Posthoc results are available upon request and are not reported here, as the anonymity of the data precludes any meaningful interpretation; however, the results are presented to demonstrate the power of these scales to detect differences among centers.

Discussion

The purpose of this paper was to examine the psychometric properties of scales that measure collaboration

Table 4. Means and SEs for the collaboration and transdisciplinary-integration scales and subscale scores by respondent's role and by center

	Role				Center						
	I	**PSS**	**S**	**O**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	***n*=100**	***n*=47**	***n*=34**	***n*=19**	***n*=22**	***n*=49**	***n*=35**	***n*=17**	***n*=28**	***n*=20**	***n*=34**
Satisfaction with collaboration	4.11 (0.07)	4.05 (0.11)	4.17 (0.12)	3.66 (0.18)	4.47 (0.14)	3.70 (0.10)	3.84 (0.11)	4.44 (0.16)	4.43 (0.12)	3.45 (0.65)	4.22 (0.11)
Impact of collaboration	3.96 (0.07)	4.11 (0.12)	4.12 (0.12)	4.05 (0.20)	4.53 (0.15)	3.57 (0.11)	3.88 (0.12)	4.09 (0.16)	4.44 (0.13)	3.61 (0.76)	4.05 (0.11)
Trust and respect	4.47 (0.06)	4.38 (0.09)	4.64 (0.10)	4.12 (0.13)	4.59 (0.12)	4.15 (0.09)	4.27 (0.10)	4.57 (0.14)	4.60 (0.11)	4.36 (0.46)	4.58 (0.10)
Transdisciplinary integration	3.95 (0.06)	4.20 (0.09)	4.10 (0.09)	4.19 (0.13)	4.15 (0.12)	3.84 (0.08)	4.12 (0.09)	3.96 (0.13)	4.28 (0.10)	3.87 (0.55)	4.16 (0.09)

Note: Scale scores range from 1 (low endorsement) to 5 (high endorsement of the construct).
I, investigator; O, other; PSS, professional support staff; S, student

and transdisciplinary integration in the context of team science. Overall, the hypothesized factor structures—with some minor modifications—were validated. A total of four scales were developed, and measured the following: perceived satisfaction with collaboration, the impact of collaboration on the research process, trust and respect in a collaborative setting, and transdisciplinary integration. All scales were found to have adequate internal consistency (i.e., Cronbach α's were all >0.70); to be correlated with most intermediate markers of ELI; and to show some ability to detect some group differences.

One of the key findings from this study is that the hypothesized factors were verified, with minor modifications (i.e., correlated-error terms were added to these solutions). Having some correlated-error terms suggests that there might be some redundancies among these items that might be important to re-examine in future administrations (e.g., collaboration Item 7, *involvement of collaborators from outside the center*, and Item 8, *involvement of collaborators from diverse disciplines*). However, it is important to note that the negatively worded items on both scales created some problems: not loading on the scale or creating spurious correlated-error terms. It is well-known that having a subset of negatively worded items leads to a methodologic artifact—either having an extraneous factor or having correlated-error terms among all negatively worded items (as observed in this paper).[29] Certainly the presence of such methodologic artifacts calls into question the common measurement practice of mixing positively and negatively worded items in the scale.[29] Because these items address an important area, they were maintained to maximize the content validity of the scale. It should be noted that the internal consistency of the scale was not adversely affected by keeping the negatively worded items in the scale.

Associations among the scales with intermediate markers of progress were presented to further evaluate the construct validity of these scales. These results suggest that those who perceived higher levels of satisfaction with collaboration and those who had an overall positive view of transdisciplinary integration also perceived that their center was making good progress in creating new methods, new science and models, and new interventions. The lack of association with the publications index is not unexpected, as cross-sectional associations were examined in Year 3 of the initiative, and the number of publications is expected to be limited at this early stage of the transdisciplinary effort. In fact, the results found a restricted range of publications (0–6 total) for the initiative.

It has been suggested that empirical efforts to link specific facets of team-based science (e.g., processes of cross-disciplinary collaboration and intellectual integration generated through center-based working groups, retreats, and training programs) with more tangible scientific and societal outcomes may require longitudinal studies that extend over 1 or more decades.[30] Team science initiatives are structurally complex, and several years are required to establish and coordinate the efforts of multiple investigators and trainees working within and across several (often geographically dispersed) centers.[10] Therefore, the results reported here must be supplemented in future years by longer-term investigations that track the scientific and societal contributions of team initiatives sustained over 1 or more decades; and must incorporate comparison groups comprising individuals or small groups of scholars working on similar scientific questions—but from outside the framework of "big science."

In closing, it should be noted that this study was limited in its ability to examine the predictive validity of these scales, as only cross-sectional data were available. Furthermore, the stability (test–retest reliability) of these scales was not assessed. Therefore, much more work is needed to further assess the utility of these scales for detecting changes over time (e.g., in the collaborative effectiveness and productivity of transdisciplinary centers); for detecting stability; and for elucidating the pathways by which team science initiatives generate longer-term impacts on scientific progress and population health as suggested by the ELI logic model. Another potential limitation of this study was that TTURC researchers may have reacted to the demand characteristics of the study by both responding in a manner that would make them appear to be working in more of a transdisciplinary manner and responding in a positive way to this type of collaborative work, especially given the financial incentive of TTURC initiatives. Nonetheless, with these caveats, this paper provides valid tools that can be utilized to examine the underlying processes of team science—an important initial step toward advancing the science-of-team-science field.

No financial disclosures were reported by the authors of this paper.

References

1. Esparza J, Yamada T. The discovery value of "Big Science." J Exp Med 2007;204:701–4.
2. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005. www.nap.edu/catalog.php?record_id=11153#toc.
3. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
4. Wuchty S, Jones BF, Uzzi B. The increasing dominance of teams in production of knowledge. Science 2007;316:1036–9. doi:10.1126/science.1136099.
5. Kessel FS, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science: case studies in interdisciplinary innovation. New York: Oxford University Press, 2003.
6. Klein JT. Crossing boundaries: knowledge, disciplinarities, and interdisciplinarities. Charlottesville VA: University of Virginia Press, 1996.
7. Stokols D. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
8. Marks AR. Rescuing the NIH before it is too late. J Clin Invest 2006;116:844.
9. NIH. NIH Roadmap for medical reseach: interdisciplinary research. 2003. nihroadmap.nih.gov/interdisciplinary/index.asp.
10. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
11. Weissmann G. Roadmaps, translational research, and childish curiosity. FASEB J 2005;19:1761–2.
12. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
13. Rhoten D, Parker A. Education: risks and rewards of an interdisciplinary research path. Science 2004;306:2046.
14. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
15. National Cancer Institute. Transdisciplinary tobacco use research centers. 2006. dccps.nci.nih.gov/tcrb/tturc/.
16. National Cancer Institute. Transdisciplinary research on energetics and cancer. 2006. https://www.compass.fhcrc.org/trec/.
17. National Cancer Institute. Health communication and informatics research: NCI centers of excellence in cancer communications research. 2006. cancercontrol.cancer.gov/hcirb/ceccr/.
18. National Cancer Institute. Centers for population health and health disparities. 2006. cancercontrol.cancer.gov/populationhealthcenters/.
19. Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
20. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
21. National Center for Health Statistics. Deaths, percent of total deaths, and death rates for the 15 leading causes of death: U.S. and each state, 2003. 2006. www.cdc.gov/nchs/data/dvs/lcwk9_2003.pdf.
22. WHO. WHO smoking statistics. 2003. www.wpro.who.int/media_centre/fact_sheets/fs_20020528.htm.
23. Trochim WM, Marcus SE, Mâsse LC, Moser RP, Weld PC. The evaluation of large research initiatives: a participatory integrated mixed-methods approach. Am J Eval 2008;29:8–28.
24. Gray B. Collaborating: finding common ground for multiparty problems. San Francisco: Jossey-Bass Publishers, 1989.
25. Gray B. Cross-sectoral partners: collaborative alliances among business, government, and communities. In: Huxham C, ed. Creating collaborative advantage. London: Sage Publications, 1996.
26. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
27. Hu L, Bentler PM. Evaluating model fit. In: Hoyle RH, ed. Structural equation modeling: concepts, issues, and applications. Thousand Oaks CA: Sage Publications, 1995.
28. Nunnally J, Bernstein I. Psychometric theory. 3rd ed. New York: McGraw-Hill, 1994.
29. Marsh HW. Positive and negative global self-esteem: a substantially meaningful distinction or artifactors? J Pers Soc Psychol 1996;70:810–9.
30. Abrams DB, Leslie FM, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res 2003;5(1S):S5–S10.

Appendix A: List of collaboration items

Item (short description)	Stem employed in the researcher survey
Satisfaction with collaboration: Items 1–8	
1. Acceptance of ideas	*Acceptance of new ideas*
2. Communication	*Communication among collaborator*
3. Strengths	*Ability to capitalize on the strengths of different researchers*
4. Organization	*Organization or structure of collaborative teams*
5. Conflict resolution	*Resolution of conflicts among collaborators*
6. Working styles	*Ability to accommodate different working styles of collaborators*
7. Outside involvement	*Involvement of collaborators from outside the center*
8. Discipline involvement	*Involvement of collaborators from diverse disciplines*
Impact of collaboration: Items 9–14	
9. Meeting productivity	*Productivity of collaboration meetings*
10. Products productivity	*Productivity in developing new products (e.g., papers, proposals, courses)*
11. Overall productivity	*Overall productivity of collaboration*
12. Research productivity	*In general, collaboration has improved your research productivity.*
13. Quality research	*In general, collaboration has improved the quality of your research.*
14. Time burden	*Collaboration has posed a significant time burden in your research.*
Trust and respect: Items 15–18	
15. Showing limits	*You are comfortable showing limits or gaps in your knowledge to those with whom you collaborate.*
16. Trust colleagues	*In general, you feel that you can trust the colleagues with whom you collaborate.*
17. Open to criticism	*In general, you find that your collaborators are open to criticism.*
18. Respect	*In general, you respect your collaborators.*

Note: Items 1–11 asked respondents to Please evaluate the collaboration within your center by indicating if the collaboration is (1) inadequate, (2) poor, (3) satisfactory, (4) good, or (5) excellent. Items 12–18 asked respondents to Please rate your views about collaboration with respect to your center-related research by indicating if you (1) strongly disagree, (2) somewhat agree, (3) not sure, (4) somewhat agree, or (5) strongly agree with the statement.

Appendix B: List of transdisciplinary integration items

Item (short description)	Stem employed in the researcher survey
1. Value collaboration	*I would describe myself as someone who strongly values transdisciplinary collaboration.*
2. Knowledge interference	*Transdisciplinary research interferes with my ability to maintain knowledge in my primary area.*
3. Less productive	*I tend to be more productive working on my own rather than working as a member of a transdisciplinary research team.*
4. Fewer publications	*In a transdisciplinary research group, it takes more time to produce a research article.*
5. Stimulates thinking	*Transdisciplinary research stimulates me to change my thinking.*
6. Changes research ideas	*I have changed the way I pursue a research idea because of my involvement in transdisciplinary research.*
7. Improved my research	*Transdisciplinary research has improved how I conduct research.*
8. Valuable science	*I am optimistic that transdisciplinary research among TTURC participants will lead to valuable scientific outcomes that would not have occurred without that kind of collaboration.*
9. Improves interventions	*Participating in a transdisciplinary team improves the interventions that are developed.*
10. Discipline contribution	*Because of my involvement in transdisciplinary research, I have an increased understanding of what my own discipline brings to others.*
11. Sustained collaboration	*My transdisciplinary collaborations are sustainable over the long haul.*
12. Outweighs inconveniences	*Generally speaking, I believe that the benefits of transdisciplinary scientific research outweigh the inconveniences and costs of such work.*
13. Comfortable environment	*I am comfortable working in a transdisciplinary environment.*
14. Effort to engage	*Overall, I am pleased with the effort I have made to engage in transdisciplinary research.*
15. Open-minded perspective	*TTURC members as a group are open-minded about considering research perspectives from fields other than their own.*

For all items, respondents were asked to *Please rate the following attitudes about transdisciplinary research by indicating if you (1) strongly disagree, (2) somewhat agree, (3) not sure, (4) somewhat agree, or (5) strongly agree with the statement.*

The Collaboration Readiness of Transdisciplinary Research Teams and Centers

Findings from the National Cancer Institute's TREC Year-One Evaluation Study

Kara L. Hall, PhD, Daniel Stokols, PhD, Richard P. Moser, PhD, Brandie K. Taylor, MA, Mark D. Thornquist, PhD, Linda C. Nebeling, PhD, Carolyn C. Ehret, MS, RD, Matthew J. Barnett, MS, Anne McTiernan, MD, PhD, Nathan A. Berger, MD, Michael I. Goran, PhD, Robert W. Jeffery, PhD

Abstract: Growing interest in promoting cross-disciplinary collaboration among health scientists has prompted several federal agencies, including the NIH, to establish large, multicenter initiatives intended to foster collaborative research and training. In order to assess whether these initiatives are effective in promoting scientific collaboration that ultimately results in public health improvements, it is necessary to develop new strategies for evaluating research processes and products as well as the longer-term societal outcomes associated with these programs. Ideally, evaluative measures should be administered over the entire course of large initiatives, including their near-term and later phases. The present study focuses on the development of new tools for assessing the readiness for collaboration among health scientists at the outset (during the first year) of their participation in the National Cancer Institute's Transdisciplinary Research on Energetics and Cancer (TREC) initiative. Indexes of collaborative readiness, along with additional measures of near-term collaborative processes, were administered as part of the TREC Year-One evaluation survey. Additionally, early progress toward scientific collaboration and integration was assessed, using a protocol for evaluating written research products. Results from the Year-One survey and the ratings of written products provide evidence of cross-disciplinary collaboration among participants during the first year of the initiative, and also reveal opportunities for enhancing collaborative processes and outcomes during subsequent phases of the project. The implications of these findings for future evaluations of team science initiatives are discussed.

(Am J Prev Med 2008;35(2S):S161–S172)

Introduction

To facilitate scientific efforts to solve complex public health problems such as cancer incidence, morbidity, and obesity-associated mortality, multidisciplinary teams of investigators drawn from a variety of different fields are being formed.[1,2] The major goals of these teams are to develop new methods, theories, and conceptual models that integrate several disciplinary perspectives. Cross-disciplinary scientific collaboration is intended to move areas of research forward in ways that individual investigators working from a single disciplinary perspective could not accomplish on their own or in a timely manner.[3,4]

Conducting team science that bridges multiple disciplines can be expensive and labor intensive.[5] Therefore, it is important to identify and understand those conditions that facilitate or hinder effective cross-disciplinary collaboration.[6] Whereas the enhancement of public health is perhaps the most crucial intended outcome of cross-disciplinary health research, identifying the gains in health status attributable to a particular research program can be quite difficult, especially during the early phases of a team science initiative. Research takes time to develop, conduct, disseminate, and implement. The stage of research and the state of the infrastructure for translating research into tangible health benefits influences the length of time it takes for these improvements to become evident at the community and societal levels. In the interim, near-term markers of successful collaboration

From the Division of Cancer Control and Population Sciences (Hall, Moser), National Cancer Institute, and the Office of Portfolio Analysis and Strategic Initiatives (Taylor), NIH, Bethesda, Maryland; the School of Social Ecology, University of California Irvine (Stokols), Irvine, California; the Cancer Prevention Program, Division of Public Health Sciences, Fred Hutchinson Cancer Research Center (Thornquist, Ehret, Barnett, McTiernan), Seattle, Washington; the Center for Science, Health & Society, School of Medicine, Case Western Reserve University (Berger), Cleveland, Ohio; the Department of Preventive Medicine, University of Southern California (Goran), Los Angeles, California; and the Division of Epidemiology and Community Health, School of Public Health, University of Minnesota (Jeffery), Minneapolis, Minnesota

Address correspondence and reprint requests to: Kara L. Hall, PhD, Health Scientist, Division of Cancer Control and Population Sciences, National Cancer Institute, 6130 Executive Boulevard, Room 4080, Bethesda MD 20850. E-mail: hallka@mail.nih.gov.

doi:10.1016/j.amepre.2008.03.035

and integration are necessary for evaluating scientific progress during a research initiative.[7] This paper presents new methods for assessing the antecedents of effective cross-disciplinary collaboration and near-term markers of collaborative processes and outcomes as evaluated during the early phase of a large-scale research and training initiative in the field of energetics and cancer.

Transdisciplinary Research on Energetics and Cancer Initiative

During the fall of 2005, the National Cancer Institute (NCI) established the Transdisciplinary Research on Energetics and Cancer (TREC) initiative comprising four research centers and one coordination center.[8] The TREC centers are intended to foster collaboration among transdisciplinary teams of scientists with the goal of accelerating progress toward reducing cancer incidence, morbidity, and mortality associated with energy imbalance, obesity, and low levels of physical activity. They also aim to conduct research to elucidate the mechanisms linking energetics and cancer and to provide training opportunities for new and established scientists who can carry out integrative research on energetics and energy balance (www.compass.fhcrc.org/trec). This $54-million initiative was created through a combination of funding mechanisms that enable four research centers to have the support of a centralized coordination center. NCI is partnering with the centers to support developmental projects both within and between centers as well as an initiative-wide evaluation process.[9]

Previous evaluation studies have assessed collaborative processes and outcomes during the mid-term or later stages of an initiative,[7,10] but to the authors' knowledge, no study to date has assessed antecedent factors present at the outset of an initiative that may influence the effectiveness of team collaboration over the duration of the program. The TREC Year-One evaluation study, summarized below, contributes to the science of team science by providing newly developed metrics for assessing collaboration-enhancing or -impairing factors present during the first year of a large-scale, cross-disciplinary research and training initiative, and for evaluating the empirical links between these antecedent conditions and near-term markers of scientific collaboration and integration.

Collaborative Readiness and Capacity

A number of circumstances can influence a team's prospects for effective cross-disciplinary collaboration during the early stages of an initiative. These factors may enhance or hinder collaborative processes during the proposal-development phase, during preparations for project launch once funding has been received, and during the initial months once the project has commenced. They may also affect the longer-term success of the collaboration, its scientific outcomes, and, ultimately, the public health impacts of an initiative. A variety of circumstances that facilitate or constrain effective teamwork during the initial stages of a project have been identified as collaborative-readiness factors in earlier evaluations of cross-disciplinary scientific projects and research centers.[6,7,11] In this discussion, at least three categories of collaborative-readiness factors are considered: (1) **contextual–environmental conditions** (e.g., institutional resources and supports or barriers to cross-departmental collaboration; the environmental proximity or electronic connectivity of investigators, or both); (2) **intrapersonal characteristics** (e.g., research orientation, leadership qualities); and (3) **interpersonal factors** (e.g., group size, the span of disciplines represented, investigators' histories of collaboration on earlier projects).

Contextual–environmental influences on collaboration (e.g., environmental proximity among investigators, bureaucratic administrative infrastructures at universities or research labs) are more hard-wired into the physical and social environment, whereas intrapersonal and interpersonal collaborative-readiness factors are, perhaps, more malleable human factors whose qualities change over time as a result of collaborative processes. Contextual factors such as geographic constraints on collaboration and institutional resources may also change over time, but these processes are perhaps more gradual and difficult to accomplish due to the rigidity of environmental and bureaucratic structures. Presumably, contextual–environmental conditions as well as intrapersonal and interpersonal factors interact with each other to influence the overall collaborative readiness of a scientific team, or the extent to which team members are likely to achieve the collaborative goals specified at the outset of the project.

Olson and Olson,[11] in their studies of collaboration among team members who are geographically dispersed, have emphasized the importance of technology readiness, or the extent to which participants have the requisite technical infrastructure and expertise to establish and sustain electronic communications and information exchange with each other. In the context of the present study, collaborative readiness is conceptualized more broadly to encompass motivational factors, leadership resources, investigators' histories of prior collaboration and informal social relations with each other, spatial proximity, electronic connectivity, and other institutional supports for centers and teams (see also Stokols et al.[5–7]). Considering the diversity of collaborative-readiness factors, it is important not only to identify the range of potential influences on teamwork but also to understand which factors exert the greatest impact on team members' collaborative processes and outcomes.

As a project moves into its mid- and later phases of development, the notion of readiness for collaboration becomes less salient or relevant. During the later stages of the project, the contextual–environmental factors, intrapersonal factors, and interpersonal factors that facilitate or constrain a team's effectiveness are better construed as determinants of collaborative capacity among investigators rather than as readiness factors that influence participants' prospects for effective collaboration primarily at the outset of an initiative. A conceptual model of the temporal relationships among collaborative-readiness factors, collaborative capacity, and collaborative outcomes is shown in Figure 1.

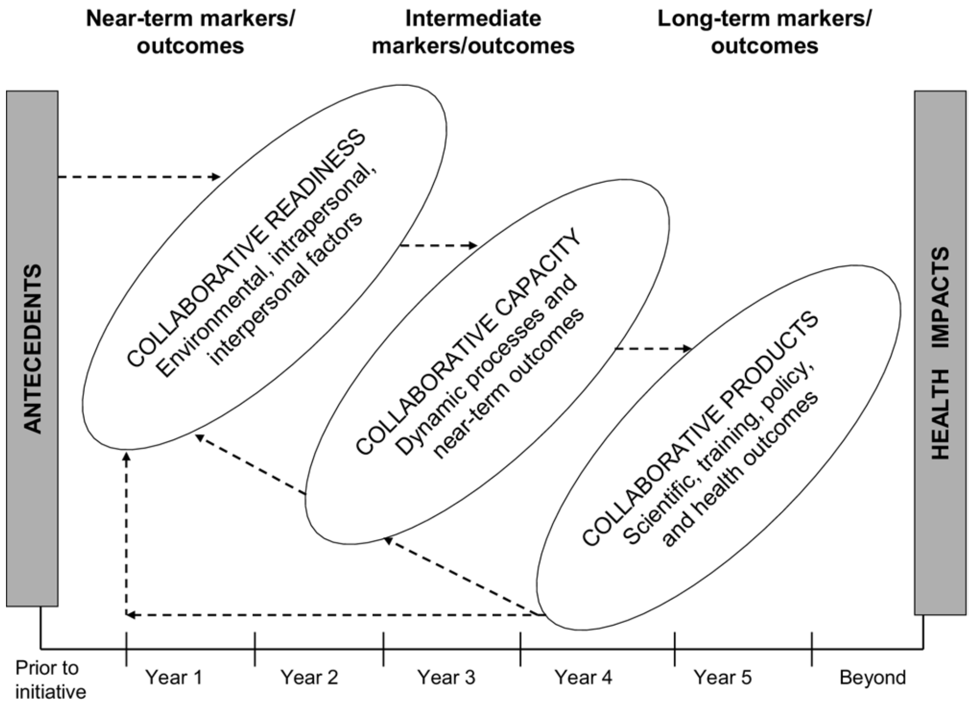


Figure 1. Conceptual model for evaluation of collaborative initiatives

Process and Product Measures of Scientific Collaboration

At least two methodologic approaches have been used for assessing the levels of cross-disciplinary collaboration and integration achieved by the members of research teams and centers. One strategy is to assess the ongoing processes of collaboration and scientific synergy as they occur within particular research and training settings such as investigators' offices, conference rooms, and laboratories. A second approach is to evaluate the cross-disciplinary qualities (e.g., the quality and scope of integration among multiple disciplinary perspectives) reflected in tangible collaborative products such as manuscripts, grant proposals, published journal articles, and books.[12] These research deliverables can serve as markers of collaborative progress during both the initial and later phases of a cross-disciplinary initiative. Although product assessments do not capture the dynamics of cross-disciplinary collaboration as it occurs over time, the development of objective criteria for evaluating the integrative scope and quality of written products has the advantage of establishing standardized criteria that can be applied reliably and validly across a wide range of research and training projects. In the current evaluation of the NCI TREC initiative, both process and product measures were used to gauge early progress toward cross-disciplinary collaboration among TREC investigators.

Two related studies are reported below. In the first, Year-One survey measures were developed and administered to assess collaborative-readiness factors and near-term (i.e., Year-One) evidence of cross-disciplinary collaboration within the TREC centers. In the second, an independent reviewer-rating protocol was designed to evaluate the integrative qualities of early-term research products—specifically, pilot project grant proposals submitted by investigators during the first year of the TREC initiative. These two components of the TREC evaluation study extend earlier research in the field of team science by providing new methods for (1) assessing collaboration readiness among the members of cross-disciplinary research teams and centers and (2) gauging progress toward scientific collaboration and integration during the initial phase of a 5-year NCI scientific centers initiative, evidenced through survey measures of collaborative processes and inter-rater evaluations of the cross-disciplinary qualities of team members' research products.

Methods of the TREC Year-One Survey

This study involved the development and implementation of a Year-One survey for measuring collaborative-readiness factors and early evidence of scientific collaboration during the first year of the TREC initiative. Development of the online Year-One survey was a collaborative effort between representatives of NCI's evaluation team and the TREC coordination center, which gathered input from TREC center directors through the TREC evaluation working group over the course of the survey's development and administration.

The TREC evaluation working group comprises members from all the TREC centers, the TREC coordination center, and the NCI evaluation team, which represents all partners within the TREC initiative cooperative agreement.

The NCI evaluation team comprises NCI-affiliated staff who participate in evaluation activities for the TREC initiative. They work with the TREC evaluation working group on relevant activities, provide content leadership that complements expertise at the TREC centers, and consider issues at the programmatic level, keeping broader evaluation interests at hand.

The TREC coordination center serves as a central resource for the TREC research centers supported by an NCI U01 grant, handling activities and functions such as central communication and evaluation activities, training, and the conduct of original research, making it more than just an administrative unit. The coordination center provided intensive support in facilitating the evaluation of the four centers, and therefore members of this center were not included as research subjects in the current evaluation.

A TREC center, or TREC research center, is an institution-based research unit supported by an NCI U54 grant. Each research center is located at a specific university or cancer center and coordinates a variety of research projects, core resources for the individual center, training activities, and developmental grants.

Participants

Investigators, including center directors, co-investigators, and research staff from the four research centers who were active in the TREC initiative at the start of data collection, were eligible for the study. As mentioned previously, because of the central role played by the coordination center in conducting the evaluation, the coordination center's investigators and staff were not included in the Year-One survey. The final sample size for the evaluation was 56 of 76 participants, resulting in a response rate of 74%.

Approval was received from the IRBs of the three agencies/institutions primarily involved in the development of the survey: the Fred Hutchinson Cancer Research Center (the coordination center); Westat Inc., the third-party contractor; and the NCI. Each respondent was presented with the online consent form before he or she received the online survey.

Survey Measures

Several new survey instruments were created for the TREC Year-One evaluation survey. Additionally, some of the measures were adapted from earlier studies of cross-disciplinary research centers and teams.[5,6,10] These measures, administered during the first 6 months of the TREC initiative, can be found online in their entirety (cancercontrol.cancer.gov/trec/TREC-Survey-2006-01-31.pdf). The major scales developed for the TREC survey are described below.

These scales are grouped into two major categories. The first category includes collaborative-readiness measures of respondents' research orientations, as well as antecedent measures of collaborative readiness including their assessments of the institutional resources available to support TREC-related activities at the outset of the initiative, their reports of prior collaboration with TREC colleagues on pre-TREC projects, and the number of years in which they had participated in interdisciplinary or transdisciplinary research centers and projects prior to the TREC initiative. The second category of measures include near-term (first 6 months) measures of collaborative processes, namely, respondents' overall impressions of their research center and their assessments of interpersonal collaboration and productivity, the cross-disciplinary activities in which they had engaged, and their expectations that their TREC-related projects would be successful in achieving their previously specified Year-One deliverables.

Measures of Collaborative-Readiness Factors

The research-orientation scale (Cronbach's α=0.74) assessed the unidisciplinary or cross-disciplinary proclivity of the investigators' values and attitudes toward research, using a 5-point scale ranging from *strongly disagree* to *strongly agree*. Previous measures of researchers' orientations asked them to describe their transdisciplinary values and behaviors; in contrast, the research-orientation scale developed for this study was designed to assess the cross-disciplinary continuum as defined by Rosenfield[13] by using items that measure each of four major research orientations: unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary.

A **unidisciplinary** research orientation is characterized by the use of theories and methods drawn from a single field, whereas cross-disciplinary (i.e., multidisciplinary, interdisciplinary, transdisciplinary) research orientations entail the combined use of concepts and methods drawn from two or more distinct disciplines. **Multidisciplinary** collaborations involve researchers who share their own disciplinary insights and perspectives with colleagues who are trained and work in fields different from their own. **Interdisciplinary** collaborations involve a higher level of integration among the different disciplinary perspectives of team members than is evident in multidisciplinary collaborations. **Transdisciplinary** collaborations, like interdisciplinary ones, strive toward the integration of two or more disciplinary perspectives, but are uniquely characterized by the creation of novel conceptualizations and methodologic approaches that transcend or move beyond the individual disciplines represented among team members. The final items included in this scale are presented in Figure 2, along with a path diagram showing the grouping of the items and their factor loadings from a confirmatory factor analysis (described below).

The history-of-collaboration scale assessed the number of investigators at the participant's TREC center with whom the participant had collaborated on prior projects (*number of collaborators*); it also assessed the participant's satisfaction with the previous collaboration with each of those individuals, using a 5-point Likert scale ranging from *not at all satisfied* to *completely satisfied* (*collaborative satisfaction rating*). Also assessed were the number of years during which the respondent had participated in interdisciplinary or transdisciplinary research centers (*number of years in inter/trans centers*) and in interdisciplinary or transdisciplinary research projects (*number of years in inter/trans projects*) prior to the TREC initiative.

The institutional-resources scale (α=0.87) assessed investigators' impressions of the availability and quality of resources (e.g., physical environment, computer support, personnel) at their centers for conducting TREC-related research. Each type of institutional resource was rated by respondents on 5-point Likert scales ranging from *very poor* to *excellent*.

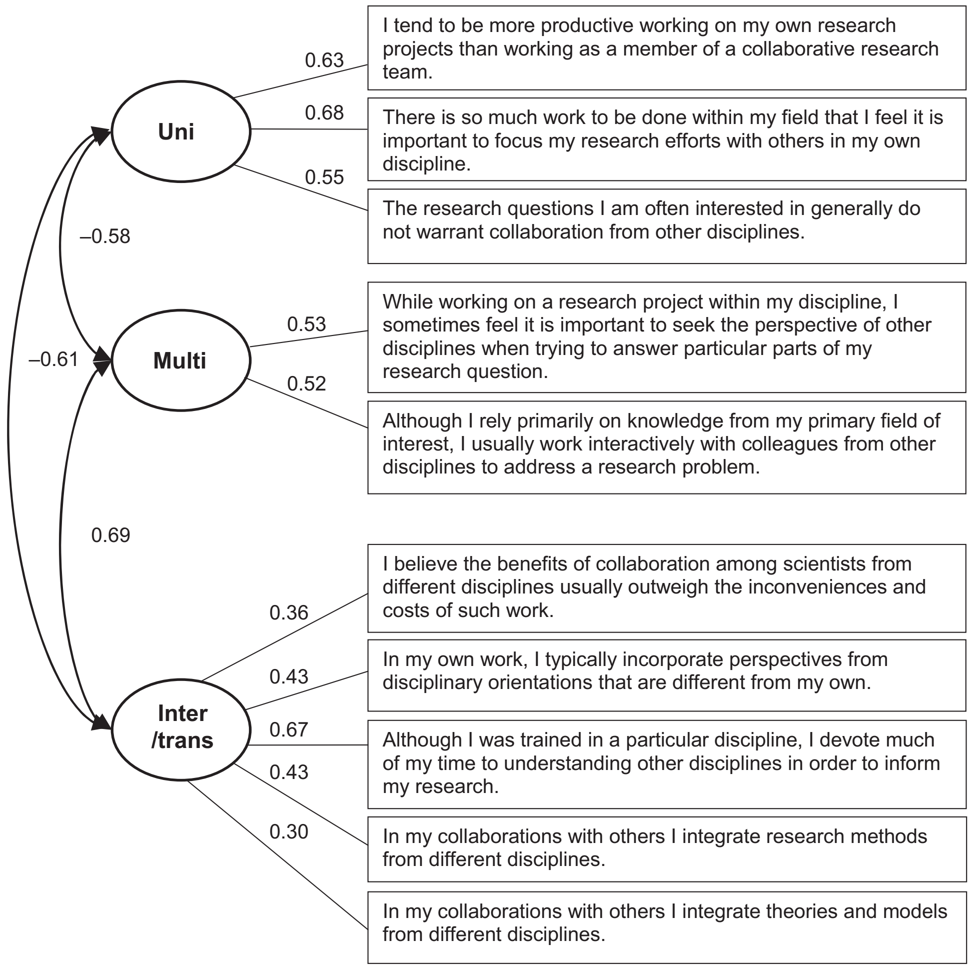


Figure 2. Path diagram for the research-orientation scale, including factor loadings and factor correlations

Near-Term Markers of Collaborative Processes

The semantic-differential/impressions scale (α=0.98) assessed investigators' impressions of their center as a whole, as well as how they feel as a member of their TREC center. The items in this scale included divergent terms listed at each end of a 7-point continuum on which respondents rated their impressions (e.g., *conflicted–harmonious*; *not supportive–supportive*; *scientifically fragmented–scientifically integrated*).

The interpersonal-collaboration scale (α=0.92) assessed investigators' perceptions of the interpersonal collaborative processes occurring at their TREC center. Examples of these interpersonal processes included conflict resolution, communication, trust, and social cohesion, rated on 5-point Likert scales ranging from *very poor* to *excellent* and from *strongly disagree* to *strongly agree*.

The collaborative-productivity scale (α=0.95) assessed investigators' perceptions of collaborative productivity within their own TREC center, including the productivity of scientific meetings and the center's overall productivity, on a 5-point Likert scale ranging from v*ery poor* to *excellent*. They were also asked to respond to the statement *In general, collaboration has improved your research productivity,* on a 5-point scale ranging from *strongly disagree* to *strongly agree*.

The cross-disciplinary collaboration-activities scale (α=0.81) assessed the frequency with which each investigator engaged in collaborative activities outside his or her primary field, such as reading journals or attending conferences outside the primary field and establishing links with colleagues in different disciplines that led to collaborative work, on a 7-point scale ranging from *never* to *weekly*.

The TREC-related collaborative-activities scale (α=0.74) assessed the frequency with which each investigator engaged in TREC-specific activities, such as collaborating with fellow members of her or his own or another TREC center on new developmental projects or on activities other than developmental projects, on a 7-point scale ranging from *never* to *weekly*.

Finally, the completing-deliverables scale assessed investigators' expectations that their research, core, and developmental projects would adhere to the agreed-upon schedule for completing Year-One deliverables, on a 5-point Likert scale ranging from *highly unlikely* to *highly likely*. All projects being conducted at the participant's center were listed, and each project was rated separately.

Survey Procedures

The TREC Year-One survey was administered to respondents via a third-party research contractor (Westat Inc.) through online administration. Participants completed the Year-One questionnaire by clicking a link—in an e-mail sent directly to them—to their individualized, password-protected survey. The survey required an average of 35 minutes to complete, and was launched 6 months after the start date of the initial award. Participants were given 8 weeks to complete the survey. Reminder e-mails were sent to those who had not completed the questionnaire at 1-, 2-, and 3-week intervals.

Analyses and Results of the TREC Year-One Survey

Analyses of the Research-Orientation Scale

The research-orientation scale is a theoretically based measure designed to assess the cross-disciplinary continuum of researchers' orientations as outlined by Rosenfield.[13] Factor analyses were conducted to determine whether the relationships among the disciplinary types were, in fact, on a continuum, or best represented as separate factors. Exploratory analyses assessed the factor structure of the research-orientation scale by (1) identifying distinct factors and estimating the correlations between them; (2) computing factor loadings; and (3) eliminating items with poor loadings and high complexity (e.g., items that loaded highly on more than one factor). The final items included in each factor were selected on the basis of factor loadings, item clarity, minimum item redundancy, and the conceptual representativeness of each factor.

Although the use of four factors would be most consistent with the underlying theoretical model, the maximum-likelihood method and principal-axis factoring resulted in an ultra-Haywood case indicating either that there were *too many common factors* or *not enough data to provide stable estimates* of four distinct factors. Given the small sample size (n=56), there is likely insufficient power to extract the four theoretically hypothesized factors, even if they do exist. Convergence was obtained when extracting three factors using direct oblique rotation employing a maximum-likelihood method. The Kaiser–Meyer–Olkin statistic (>0.6) predicts that the data are suitable for the factor analysis of three factors. The nonsignificance (p=0.103) of the goodness-of-fit test shows that the three-factor model fits well.

Following this, a confirmatory factor analysis was conducted, based on the theoretical underpinnings of the research-orientation scale and the results of the exploratory-factor analysis. Four items were excluded from the model due to low loadings, double loadings on meaningful factors, or conceptual inconsistency. Three alternative models were examined and compared, based on theoretical conceptualizations of the model. The goodness-of-fit indexes for the confirmatory factor analysis were all within the range of 0–1. The final model included three factors with acceptable goodness-of-fit (CFI=0.95, SRMR=0.073, and RMSEA=0.00; CI=0.0, 0.099). A path diagram of the final model, including factor loadings and items, is shown in Figure 2.

Bivariate Correlations

The Pearson correlation coefficients among key study variables are listed in Table 1. Means and ranges for the variables are also included there. Key associations among research-orientation scale factors are described below.

Research-orientation scale. Those participants who scored higher on the unidisciplinary factor engaged in fewer cross-disciplinary collaborative activities. Additionally, those who scored higher on the unidisciplinary factor scored lower on both the multidisciplinary and interdisciplinary/transdisciplinary factors. Those who scored higher on the multidisciplinary factor tended to engage in more cross-disciplinary and TREC-related collaborative activities, had more collaborators, reported better collaborative productivity at their center, and perceived more institutional resources. Those who scored higher on the interdisciplinary/transdisciplinary factor engaged in more cross-disciplinary and TREC-related collaborative activities, and were also found to score higher on the multidisciplinary factor.

History of interdisciplinary/transdisciplinary centers and projects. The fewer the number of years of involvement in interdisciplinary/transdisciplinary centers and projects, the fewer the number of collaborators the participants reported having, and the more likely they were to believe that Year-One deliverables would be completed on time. Additionally, the fewer the number of years of involvment in interdisciplinary/transdisciplinary projects, the more positively the respondents rated their interpersonal collaborations, their collaborative productivity, their impressions of their centers, and their participation as a center member.

Institutional resources. The better the researcher judged his or her center's institutional resources to be, the more positive were her or his impressions of the center and the more satisfied he or she was with previous collaborators. Additionally, the better a respondent's perceptions of institutional resources, the more positively he

Table 1. Bivariate correlations, means, and ranges of key Year-One survey-study variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
# of collaborators	—	−0.22	0.25	0.46**	−0.01	−0.21	0.38**	0.42**	−0.08	−0.19	−0.17	0.09	0.36*	0.36*
Collaboration satisfaction		—	0.20	−0.03	0.09	0.34*	−0.04	0.04	0.31*	0.43**	0.40**	−0.02	0.04	0.02
Cross-disciplinary collaboration activities			—	0.20	0.20	0.04	0.23	−0.13	0.26	0.19	0.23	−0.35*	0.52**	0.45**
TREC collaboration activities				—	0.12	0.08	0.01	−0.01	0.28	0.10	0.09	0.00	0.32*	0.34*
Completing deliverables					—	0.09	−0.32*	−0.35*	0.39**	0.28*	0.35*	−0.18	−0.02	−0.01
Institutional resources						—	0.08	0.00	0.30*	0.41**	0.48**	−0.05	0.30*	0.08
# yrs inter/trans centers							—	0.51**	−0.18	−0.17	−0.14	0.09	0.10	0.14
# yrs inter/trans projects								—	−0.39**	−0.30*	−0.32*	−0.01	−0.08	0.11
Impressions									—	0.84**	0.84**	−0.06	0.17	−0.01
Interpersonal collaboration										—	0.88**	−0.09	0.06	−0.07
Collaboration productivity											—	−0.13	0.25	0.04
Unidisciplinary												—	−0.32*	−0.28*
Multidisciplinary													—	0.50**
Interdisciplinary/transdisciplinary														—
M	7.72	4.55	4.97	3.56	4.30	4.19	4.96	10.31	5.63	4.32	4.26	3.82	4.54	4.26
(Range)	(1–21)	(3.5–5)	(3–6.7)	(1–6)	(1–5)	(2.4–5)	(0–20)	(0–45)	(1.9–7)	(1.5–5)	(1–5)	(1.7–5)	(3–5)	(3–5)

Note: n ranges from 45 to 56; dashes indicate a correlation of 1.0
*$p<0.05$; **$p<0.01$
#, number; inter, interdisciplinary; trans, transdisciplinary; TREC, Transdisciplinary Research on Energetics and Cancer; yrs, years

Table 2. Significant predictors ($p<0.10$) from stepwise regression analysis for outcome: cross-disciplinary collaboration activities[a]

Variable	Parameter estimate	Pr>|t|
Multidisciplinary factor	0.58	0.010
Transdisciplinary factor	0.44	0.090

Note: R-square=0.310; n=45; df=2, 42
[a]Higher scores indicate more cross-disciplinary collaborative activities.

or she rated collaborative productivity and interpersonal collaboration within the respective center.

Regression Analyses of Year-One Survey Data

The correlational and factor analyses summarized above provided a basis for exploring potential associations between nine predictor variables and three outcome variables. The predictors included *institutional resources, years in interdisciplinary/transdisciplinary centers, number of collaborators, collaboration productivity, interpersonal collaboration, collaboration satisfaction rating, unidisciplinary factor, multidisciplinary factor,* and *interdisciplinary/transdisciplinary factor.* The following outcomes were included: *cross-disciplinary collaboration activities, semantic-differential/impressions scale,* and the *completing-deliverables scale.* Given the exploratory nature of the analysis and to help ensure that the models were not over-parameterized, stepwise regression was used to identify significant predictors. To identify potentially significant independent variables in this exploratory analysis, a criterion of $p\leq0.10$ was used.

Tables 2–4 summarize the significant findings from the regression analyses. As shown in Table 2, the higher the ratings on multidisciplinary and interdisciplinary/transdisciplinary factors, the more cross-disciplinary activities the participant was engaged in. Also, as shown in Table 3, the fewer the number of years a participant had spent in interdisciplinary/transdisciplinary projects prior to the TREC initiative, the more positive the impressions of the respective TREC center and feelings as a member of that particular center, and the higher the ratings of collaborative productivity and interpersonal

Table 3. Significant predictors ($p<0.10$) from stepwise regression analysis for outcome: investigators' impressions of their TREC center and as a TREC member (semantic/differential impressions scale)[a]

Variable	Parameter estimate	Pr>|t|
Collaboration productivity scale	0.63	0.008
Interpersonal collaboration scale	0.64	0.018
Number of yrs of inter/trans centers	–0.17	0.099

Note: R-square=0.753; n=45; df=3, 41
[a]Higher scores indicate more positive impressions of center.
inter, interdisciplinary; trans, transdisciplinary; TREC, Transdisciplinary Research on Energetics and Cancer; yrs, years

Table 4. Significant predictors ($p<0.10$) from stepwise regression analysis for outcome: investigators' completing-deliverables scale[a]

Variable	Parameter estimate	Pr>|t|
Number of yrs of inter/trans centers	−0.030	0.049
Collaboration-productivity scale	0.298	0.087

Note: R-square=0.195; n=45; df=2, 42
[a]Higher scores correspond to more optimism of completing deliverables.
inter, interdisciplinary; trans, transdisciplinary; yrs, years

collaborative processes within the center. Table 4 indicates that the more favorably participants rated the collaboration productivity of their center, the more likely it was that they thought that the Year-One deliverables would be completed on time and that they had spent fewer years as members of interdisciplinary/transdisciplinary research centers prior to the TREC initiative.

Methods of the Written Products Protocol

Rating the Cross-Disciplinary Qualities of Developmental Proposals

To assess the near-term outcomes of cross-disciplinary collaboration and productivity, a written products protocol (cancercontrol.cancer.gov/trec/TREC-Protocol-2006-09-27.pdf) was developed for evaluating the integrative qualities and scope of TREC developmental-project proposals. Each TREC center was allotted $250,000 of developmental funds (for which investigators apply through an internal application process, receiving final approval by the TREC steering committee). These funds are intended, in part, to support TREC members' efforts to facilitate collaborative research above and beyond what was originally proposed in each team's individual application for establishing a TREC center at its institution. Developmental research projects are intended to provide an avenue for integrating the conceptual and methodologic perspectives of TREC investigators trained in different fields. The timing of this analysis, using only developmental project proposals submitted during the first 6 months of the initiative, meant that no cross-center proposals were included; the first call for cross-center proposals came later in the initiative.

Protocol Criteria

Members of the NCI evaluation team created evaluation criteria for assessing the degree of cross-disciplinary integration and the conceptual breadth or scope of the proposed developmental projects. These criteria were adapted from the written products protocol developed by Mitrany and Stokols[12] to assess the cross-disciplinary scope of doctoral dissertations conducted in an interdisciplinary graduate program. The dimensions of cross-disciplinarity assessed included: disciplines represented in the content of the proposal; levels of analysis reflected in the proposed research (i.e., molecular and cellular; individual, group, and interpersonal; organizational and institutional; community and regional; societal; national; and global); the type of cross-disciplinary integration reflected in each proposal (i.e., unidisciplinarity, multidisciplinarity, interdisciplinarity, or transdisciplinarity); the scope of transdisciplinary integration reflected in each proposal (i.e., the breadth or extent to which there is integration of analytic levels, analytic methods, and discipline-specific concepts, rated on a 10-point Likert scale ranging from *none* to *substantial*); an overall assessment of the general scope of each proposal (i.e., its breadth, or the extent to which various disciplines are represented and investigators from different disciplines, analytic levels, and analytic methods are included in the proposal, rated on a 10-point Likert scale ranging from *none* to *substantial*).

Procedures for Reviewing TREC Developmental Project Proposals

Independent assessments of each developmental proposal were completed by two independent reviewers using the TREC written-products protocol. A total of 21 proposals submitted during Year One of the TREC initiative were assessed. The reviewers were trained by members of the evaluation team to ensure consistent interpretations and applications of the written-products rating scales. Consensus conference calls were later held with a moderator and members of the NCI evaluation team. Members of the evaluation team included individuals with a wide range of cross-disciplinary clinical and research experience, as well as previous experience conducting evaluations of other large transdisciplinary initiatives. Discrepant scores on the various rating scales for each proposal were discussed among the group until consensus was reached.

Analyses and Results of the Written Products Protocol

Inter-Rater Reliabilities

Inter-rater reliabilities based on Pearson's correlations ranged from 0.24 to 0.69 across the different rating scales. The highest reliabilities were identified for the ratings of experimental types (0.69); the number of analytic levels (0.59); disciplines (0.59); the general scope reflected in the proposals (0.52); and the methods of analysis (0.41). The lowest inter-rater reliability (0.24) was found when the reviewers attempted to identify the specific type of cross-disciplinary integration reflected in the various proposals.

Table 5. Bivariate correlations among key written-products study variables

	1	2	3	4	5	6
Cross-disciplinary integration type	—	0.68**	0.40*	0.21	0.20	0.37
General scope		—	0.90**	0.74**	0.38	0.67**
Total proposal disciplines			—	0.70**	0.31	0.65**
Total proposal analysis levels				—	0.49*	0.62**
Total proposal experiment types					—	0.69**
Total methods of analysis						—

Note: N=21; dashes indicate a correlation of 1.0
*$p<0.05$; **$p<0.01$

Descriptive Statistics

Disciplines represented within the developmental proposals. The average number of disciplines represented in the proposals was 3.7 (range 2.0–6.0); 43 % of the proposals included three disciplines, whereas 14 % of the proposals included two, four, five, or six disciplines. More than 35 different disciplines were represented across the 21 proposals.

Levels of analysis included in the developmental proposals. Four levels of analysis were identified across the proposals: molecular and cellular; individual; group and interpersonal; and community and regional.

Types of cross-disciplinary integration reflected in the proposals. Fourteen of the developmental proposals were identified by the raters as being interdisciplinary; six were classified as unidisciplinary; one was rated as being multidisciplinary; and none was judged to be transdisciplinary.

Cross-center collaboration. No proposals were found to include researchers or resources from more than one TREC center.

Correlations among dimensions of cross-disciplinarity. Significant correlations among the dimensions of cross-disciplinarity, assessed for each of the 21 developmental proposals, are reported in Table 5. Generally, the higher the number of disciplines reflected in a proposal, the broader its integrative scope ($r=0.90$) and the larger its number of analytic levels ($r=0.70$), as rated by independent reviewers of the proposal. Also, the higher the type of cross-disciplinarity—per Rosenfield's continuum[13]—reflected in a proposal, the broader its overall scope was judged to be ($r=0.68$).

Discussion

This study contributes to the science of team science by (1) developing and testing new evaluation research tools (i.e., the TREC Year-One survey and the written-products protocol); and (2) by opening new avenues of investigation for evaluating the empirical links between collaboration readiness and near-term collaborative processes and products in the context of large-scale, cross-disciplinary research and training initiatives. The overall response rate for the TREC Year-One survey was 74%, but the overall sample size for this initial phase of the TREC evaluation study was relatively small (i.e., $n=56$ survey participants; $n=21$ developmental proposals). Given the small sample size, the analyses should be considered exploratory and the results preliminary.

The measures developed for the Year-One survey demonstrated good internal reliability (α range=0.74–0.98). The most novel measure developed in this study was the research-orientation scale, designed to assess the four facets of disciplinary collaboration ranging from unidisciplinarity to transdisciplinarity. Analyses clearly demonstrated that there are distinct factors within this scale, although—likely owing to the small sample size—it is not clear whether this scale represents four distinct factors as conceptualized by Rosenfield[13] or if three factors (unidisciplinary, multidisciplinary, and interdisciplinary/transdisciplinary) better represent the cross-disciplinary continuum. Interestingly, there is an ongoing debate in the science of team science literature about the differentiation between interdisciplinary and transdisciplinary collaboration.[14,15] Overall the current study found that those who scored higher on the unidisciplinary factor scored lower on the multidisciplinary and interdisciplinary/transdisciplinary factors. Additionally, the cross-disciplinary aspects of the scale, the multidisciplinary and the transdisciplinary factors, were most strongly related.

The empirical associations observed in this study between the research-orientation–scale factors and other survey scales provide additional support for the conceptual factors, and shed light on scientists' attitudes toward cross-disciplinary collaboration. For instance, those who scored higher on the unidisciplinary factor reported fewer cross-disciplinary collaborative activities, whereas those ranked higher on the multidisciplinary and interdisciplinary/transdisciplinary factors reported more cross-disciplinary and TREC-related collaborative activities. These relationships were corroborated through additional regression analyses. The reported finding that an investigator's cross-disciplinary research orientation is related to greater engagement in cross-disciplinary activities (on a self-reported index of collaborative behaviors) offer preliminary cross-validation of the conceptual assumptions underlying the development of the research-orientation scale. Additional support for these relationships involves the number of collaborators associated with the three research-orientation–scale factors. Those who scored higher on the multidisciplinary and interdisciplinary/transdisciplinary factors reported more collaborators prior to TREC, whereas the unidisciplinary factor was not associated with the number of collaborators prior to TREC. The inverse relationship between scores on the unidisciplinary and the multidisciplinary and interdisciplinary/transdisciplinary factors implies that they may be mutually exclusive. Further examinations of these factors should aim to confirm this hypothesis. A logical next step would be to investigate whether individuals who begin a transdisciplinary initiative like TREC with a unidisciplinary orientation change over time as they engage in transdisciplinary collaborations.

It was also found that those who scored higher on the multidisciplinary factor felt that their center had more institutional resources. This finding suggests either that investigators with more resources might be better equipped to engage in collaborative endeavors with researchers in disparate disciplines, or that working with investigators from other disciplines might increase available resources. Future research is needed to further understand this relationship.

The number of years a researcher had been involved in pre-TREC interdisciplinary/transdisciplinary centers and projects revealed interesting associations among collaborative attitudes that may reflect certain challenges inherent in interdisciplinary/transdisciplinary collaboration. For instance, the fewer years a researcher had been involved in interdisciplinary/transdisciplinary projects prior to the TREC initiative, the more positive were his or her attitudes toward the respective TREC center's collaborative productivity and interpersonal collaboration; his or her impressions of the center; and her or his feelings as a member of that center. Inversely, this finding suggests that those respondents who reported a greater number of years involved in interdisciplinary/transdisciplinary centers and projects rated these attitudinal factors less positively. A possible interpretation of this finding is that it reflects respondents' realistic understanding of the substantial time and energy required to develop interpersonal, physical, and funding infrastructures for scientific collaboration. Alternatively, the more experienced investigators in cross-disciplinary initiatives may be more likely to perceive the TREC project as laborious and time-consuming compared to other program projects (e.g. P01, P50, or multisite trials) that may be funded at their centers. Despite these findings, it is important to note that the majority of responses by the participants were in the upper range of the scale; that is, overall the investigators rated their experiences quite positively (see means and ranges in Table 1).

Investigators' perceptions of greater institutional resources at their TREC centers were related to a more positive outlook for a variety of collaborative processes and outcomes (e.g., as reflected in their more-positive ratings of their center, their confidence in achieving transdisciplinary research and training goals, the collaborative productivity of their center, and the interpersonal qualities of their collaborations). Perhaps institutional resources provide a stable foundation for researchers that enable them to more effectively address the challenges of cross-disciplinary science and training. Moreover, not having to compete for scarce resources may facilitate greater trust and cohesion among center members as well as more favorable assessments of the lead principal investigators. Importantly, feelings of trust are an essential prerequisite for effective collaboration in cross-disciplinary teams.[6,16–18]

Finally, the collaborative-productivity and interpersonal-collaboration scales included in the Year-One survey were associated with investigators' more positive overall impressions of their center and more favorable feelings as members of the center. These associations suggest that the more favorably an investigator perceives the productivity and interpersonal relationships in a center, the more positive will be her or his overall assessment of the center. It remains to be determined in future studies whether more positive assessments and interpersonal relationships among members of a cross-disciplinary center result in higher levels of research productivity and more significant, longer-term impacts on science and society.

Turning to the ratings of the TREC investigators' developmental proposals, the written products protocol revealed evidence of successful collaboration and disciplinary integration during the first year of this large-scale, cross-disciplinary initiative. Within the 21 proposals submitted during the first 6 months of the initiative, more than 35 disciplines and four levels of analysis were represented. Thus, during the start-up phase of the TREC initiative, investigators not only had been able to launch their initially proposed research programs but also had made considerable progress in developing new collaborative studies, many of which were judged by independent reviewers as being broadly interdisciplinary in scope. The lack of proposals of a transdisciplinary nature is most likely due to the constraints of doing this work so soon after the initiative was funded. It is anticipated that analyses of subsequent developmental proposals in future years of the initiative will find them more transdisciplinary in their scope and orientation. Due to its timing, the near-term analysis of developmental project proposals was limited to within-center projects; efforts by NCI, the TREC coordination center, and the TREC steering committee have been ongoing to support collaboration among the members of multiple TREC centers. An initial review of the developmental-project proposals submitted after the completion of these analyses indicated that cross-center collaborations were already taking place.

Limitations and Future Directions

As noted earlier, the results of this study are necessarily exploratory and preliminary due to the small size of the study sample. Future investigations should incorporate both larger sample sizes and other cross-disciplinary groups of researchers to validate this study's results, especially those analyses using the research-orientation scale and the regression models. Additionally, measures of collaborative readiness and the written products protocol should also be administered across multiple initiatives in order to more firmly establish the psychometric properties of the scale and to assess its applicability across multiple research teams and settings. In fact, the research-orientation–scale protocol developed in this study is currently being administered to investigators participating in another large-scale, NCI cross-disciplinary initiative. Along these lines, an important direction for future research is to enlarge the research-orientation–scale item pool to ensure that the conceptual underpinnings of the scale are well represented, increasing the number of items per factor and maximizing the factor loadings. For instance, the inclusion of additional interdisciplinary items might increase the likelihood of identifying interdisciplinarity and transdisciplinarity as separable factors in a larger sample.

The response rate to the Year-One survey was lower than expected. Although evaluation was explicitly indicated in the cooperative agreement for the initiative and included as a role for the coordination center, many investigators felt that they were not aware of the evaluation component as intended before committing to participate in the grant submission, and thus possibly did not have buy-to the importance of participating in the evaluation; they also reported feeling that the communication regarding the specific evaluation efforts conducted in the first year was not sufficient, and that an adequate participatory process was not used to fully engage all investigators. Confidentiality agreements limit the capacity at this time to more clearly differentiate who did not respond to the survey. Some hypotheses include suppositions that the nonresponders were "loner" investigator types, were individuals with a small percentage of time to devote to the TREC initiative, or were individuals overburdened by starting up projects. Therefore it is unclear if the nonresponders were not ready to engage in transdisciplinary research collaboration or simply were not ready to engage in evaluation efforts perceived as peripheral to their scientific mission.

Another methodologic limitation imposed by the small sample size was the difficulty of conducting analyses linking the Year-One survey data with the developmental proposal ratings. Twenty-six individuals listed as investigators in the 21 developmental proposals had also completed the Year-One survey. These researcher/proposal pairs were used to explore the relationships between participants' self-reports of collaborative readiness and the independent reviewers' external ratings of developmental project proposals in terms of their cross-disciplinary integration and overall scope. Significant associations between the survey responses and the proposal ratings were negligible, possibly due to the small number of investigators for whom both survey and proposal data were available.[a]

The written-products protocol assesses behavioral evidence of cross-disciplinary integration that can be gathered over the course of an initiative to gauge changes in the quantity and qualities of collaborative products. The consensual rating procedure used in this study suggests that reviewers' assessments of the development proposals were ultimately reliable. However, the inter-rater reliabilities of the reviewers prior to the consensus process were somewhat low, thereby potentially limiting the generalizability of this protocol to other research teams and settings. In some cases, the reviewers were challenged by the breadth of the scientific content of the proposals, which increased the need for the consensus process. It is recommended that additional refinements be made to this tool in order to enhance the clarity of the protocol criteria and the levels of inter-rater reliability on each evaluative dimension. More detailed descriptions of the criteria and the inclusion of concrete examples (e.g., narrow vs broad integrative scope) are likely to facilitate greater accuracy and consistency of reviewers' ratings of research products in future studies.

An additional limitation of this study is the retrospective measurement of antecedents and the collection of baseline data several months into the award cycle. Unfortunately, the timing of the award and the necessity of involving the coordination center and other TREC members in planning the evaluation study precluded starting the evaluation from Day 1. It was not possible to know what centers or groups of investigators were going to be funded before they received the award. Also, in order to establish buy-in of the investigators for the evaluation, time was needed for the participatory development of the baseline measures. If baseline measurement at the immediate onset of the award is desired, then a participatory process cannot occur and it is likely that a mandate for evaluation by

[a]Also, the fact that some of the developmental-project proposals already had been outlined as part of the original parent proposal submitted to NCI, while others were created after the TREC centers were launched, precluded analyses of the temporal links between collaboration readiness during the start-up phase of a center and the integrative qualities of collaborative projects that were presumed to have been initiated once the TREC initiative was underway.

the funding agency can have alternative impacts and limitations that will need to be taken into account.

The coordination center is a unique and important feature of this initiative, but because of its role in facilitating the evaluation and given its priorities on administration over scientific research, the coordination center itself was not evaluated. Therefore, this decision was based primarily on resource and potential-bias issues. In future studies, the broader evaluation of the structural organization of the initiative as well as the collaborative factors relevant to the coordination center should be examined. This would be accomplished best through an evaluation process conducted fully by a team external to the initiative.

In conclusion, this study was conducted during the start-up phase of a 5-year, transdisciplinary center initiative. Subsequent studies will be needed to determine the empirical links between collaborative-readiness factors at the outset of an initiative and subsequent collaborative processes and outcomes. Further investigations are needed to identify the highest leverage determinants of collaboration readiness and capacity—that is, those that are linked most closely to important scientific and health advances as they emerge over the course of a team science initiative. A broader understanding of the relationships among collaborative-readiness factors, collaborative capacity, and longer-term collaborative impacts on health science, clinical practice, and population well-being will enable funding agencies to more effectively identify and support the teams of researchers with the greatest potential to succeed in complex cross-disciplinary research.

This article is based on a paper presented at the National Cancer Institute Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research on October 30–31, 2006, in Bethesda MD. This research was supported by an Intergovernmental Personnel Act (IPA) contract to Daniel Stokols from the Division of Cancer Control and Population Sciences of the NCI; by Cancer Research and Training Award fellowships to Kara L. Hall and Brandie K. Taylor; and by the NCI TREC initiative. Additionally this research was supported by the following TREC-center grants funded by the NCI: U01 CA-116850-01; U54 CA-116847-01; U54 CA-116867-01; U54 CA-116848-01; and U54 CA-116849-01.

No other financial disclosures were reported by the authors of this paper.

References

1. Kessel FS, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science: case studies in interdisciplinary innovation. New York: Oxford University Press, 2003.
2. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005. www.nap.edu/catalog.php?record_id=11153#toc.
3. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–S150.
4. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
5. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
6. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
7. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
8. National Cancer Institute. Transdisciplinary research on energetics and cancer. 2006. https://www.compass.fhcrc.org/trec/.
9. Hall KL, Stokols D, Moser RP, Thornquist M, Taylor BK, Nebeling L. The collaboration readiness of transdisciplinary research teams and centers: early findings from the NCI TREC baseline evaluation study. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD.
10. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008;35(2S):S151–S160.
11. Olson GM, Olson JS. Distance matters. Human-Computer Interaction 2000;15(2/3):139–78.
12. Mitrany M, Stokols D. Gauging the transdisciplinary qualities and outcomes of doctoral training programs. J Plan Educ Res 2005;24:437–49.
13. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
14. Mabry PL, Olster DH, Morgan GD, Abrams D. Interdisciplinary and system science to improve population health: a view from the NIH Office of Behavioral and Social Sciences Research. Am J Prev Med 2008;35(2S):S211–S224.
15. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
16. Jarvenpaa SL, Leidner DE. Communication and trust in global virtual teams. Organizational Science 1999;10:791–815.
17. Mayer RC, Davis JH, Schoorman FD. An integrative model of organizational trust. Acad Manage Rev 1995;20:709–34.
18. Sonnenwald DH. Managing cognitive and affective trust in the conceptual R&D organization. In: Houtari M, Iivonen M, eds. Trust in knowledge management and systems in organizations. Hershey PA: Idea Publishing, 2003.

Transdisciplinarity Among Tobacco Harm–Reduction Researchers

A Network Analytic Approach

Keith G. Provan, PhD, Pamela I. Clark, PhD, Timothy Huerta, PhD

Abstract: Progress in tobacco control and other areas of health research is thought to be heavily influenced by the extent to which researchers are able to work with each other not only within, but also across disciplines. This study provides an examination of the extent to which researchers in the area of tobacco harm reduction work together. Specifically, data were collected in 2005 from a national group of 67 top tobacco-control researchers from eight broadly defined disciplines representing 17 areas of expertise. Network analysis was utilized to examine the extent to which these researchers were engaged in research that was interdisciplinary or transdisciplinary, based on the outcome or product attained. Findings revealed that interdisciplinary network ties were much denser than transdisciplinary ties, but researchers in some disciplines were more likely to work across disciplines than others, especially when synergistic outcomes resulted. The study demonstrates for the first time how tobacco-control researchers work together, providing direction for policy officials seeking to encourage greater transdisciplinarity. The study also demonstrates the value of network-analysis methods for understanding research relationships in one important area of health care.
(Am J Prev Med 2008;35(2S):S173–S181) © 2008 American Journal of Preventive Medicine

Introduction

In tobacco control, as in other areas of health promotion, it is becoming increasingly apparent that in order to make significant progress, a systems approach must be utilized.[1,2] In particular, those who work in discrete areas of tobacco control, like public policy or treatment or aerosol chemistry, must not only recognize the value of the contributions of those in other fields, like smoking topography, economics, and genetics, but they must also learn to work across disciplines in order to coordinate their activities and behaviors. There are increasing pressures to have basic and applied scientists work together to improve clinical and population health practices and outcomes. An idea gaining greater traction is that cross-disciplinary collaborations facilitate exposure to different theories, methodologies, approaches, and research traditions that will result in better-quality science, increased innovation, and the accelerated translation of evidence into practice.[3] Concepts such as collaboration, networks, cross-disciplinary research, and knowledge translation are changing the way scientists, practitioners, and policymakers think about the health-research enterprise.[4]

One key element of a systems approach is working collaboratively through a network.[2] A network comprises three or more individuals or organizations that are connected through any type of tie, such as friendship, resource-sharing, or work interactions. Ties may range from tightly to loosely coupled,[5] may be formally (such as transdisciplinary tobacco use research centers) or more informally structured, and may be goal-directed or serendipitous.[6] In health research, collaborative networks can occur in many different ways and involve many different types of individuals and organizations, ranging from those who conduct basic research to those who make policy and provide funding, to those who provide actual treatment and related services. A truly integrated system would involve a network of collaborative efforts that spans all areas of research and practice within a given health field and involves all key individuals and organizations. While such a system may be a long way off, and in practice may not even be possible, it is not unreasonable to work toward a goal of building greater network integration as a way of enhancing tobacco-control efforts.

One area of tobacco control that lends itself especially well to collaborative efforts is research.[7] Although

From the School of Public Administration and Policy, University of Arizona (Provan), Tucson, Arizona; Tilburg University (Provan), Tilburg, the Netherlands; the Department of Public and Community Health, University of Maryland College Park School of Public Health (Clark), College Park, Maryland; Rawls College of Business, Texas Tech University (Huerta), Lubbock, Texas; and the Child and Family Research Institute (Huerta), Vancouver, British Columbia, Canada

Address correspondence and reprint requests to: Keith G. Provan, PhD, 405 McClelland Hall, Tucson AZ 85721. E-mail: kprovan@eller.arizona.edu.

 doi:10.1016/j.amepre.2008.05.015

cross-disciplinary collaboration has always been a fundamental part of creating good research, disciplinary boundaries and narrowly defined areas of expertise often result in silos of researchers who do not work together across disciplinary boundaries or even talk with one another to share ideas.[8] Each discipline has its own theoretical perspectives, jargon, and tools and methods— differences that must be overcome for transdisciplinary teams to make progress. Thus, the content and outcomes of research are heavily affected by the process, which is dependent on the network of interactions among researchers.

The IOM has called for a shift to research that engages investigators from multiple fields in order to "capitalize on expanding knowledge of how genetic, social, and environmental factors interact to influence health."[9] Calls for greater cross-disciplinary collaboration have become an important part of the research agenda of major government-research funding agencies. For instance, several institutes of the NIH and the Robert Wood Johnson Foundation have jointly funded center grants to support Transdisciplinary Tobacco Use Research Centers (TTURC),[10] with actual and planned investments of $145.5 million between 1999 and 2009 (G. Morgan, NCI Tobacco Control Research Branch, personal communication, 2006).

Cross-Disciplinarity in Networks

While cross-disciplinary research networks have received a good deal of attention as a preferred mechanism for addressing complex problems, very little is known about the nature of collaboration among researchers. Stokols and co-workers[11] have provided a conceptual framework for evaluating transdisciplinary science, and have examined the contextual circumstances faced by participating researchers in several TTURCs, providing a foundation for evaluating the outcomes of transdisciplinary science centers.

Even less is known about the extent of transdisciplinary research that occurs across informal networks outside of funded centers. This lack of knowledge is somewhat surprising, given the importance of the topic and the explosive growth of social-network research in recent years.[6,12] In particular, very little has been done to understand the extent to which research in tobacco control or other scientific endeavors is cross-disciplinary, and if so, what this process looks like. Such knowledge would be extremely helpful not only to those who study research and knowledge-translation networks but also to those who fund, administer, and work in research networks by providing a set of guidelines or best practices for effective network organization, development, and administration.

Cross-disciplinary network interactions and involvement have been especially important in the area of tobacco harm reduction, which has been defined by Stratton et al.[13] as "minimizing harms and decreasing total morbidity and mortality, without completely eliminating tobacco and nicotine use." Because tobacco use is a complex problem—involving such things as tobacco-smoke chemistry, behavior of use, economics and public policy, and epidemiology, among others—researching harm reduction is by definition multidisciplinary. The research presented here is an examination of the extent to which researchers in tobacco harm reduction work together across disciplines, and what outcomes occur as a result. In general, the idea is that research needs to be understood as a network-level phenomenon, involving multiple individuals who work across disciplinary boundaries and develop products and outcomes that could not be attained by working independently.

This research is exploratory and was guided by several research questions. First, what are the nature and extent of the working relationships among the top research scientists who study tobacco use? Second, do tobacco-control researchers collaborate across, as well as within, academic disciplines, and if so, what is the structure of such interdisciplinary networks? Third, what outcomes are achieved through interdisciplinary network collaboration? And fourth, is the tobacco harm–reduction network achieving transdisciplinarity, and what is the structure of this network?

While there seems to be general agreement among those who study the topic that cross-disciplinary research is highly desirable as a way to advance science,[3] there is a lack of clarity on the use of the terms *multidisciplinary*, *interdisciplinary*, and *transdisciplinary*. A useful description of these three forms of cross-disciplinary research has been provided by Rosenfield,[14] whose work is summarized by Stokols et al.[15] in the introductory paper of this supplement to the *American Journal of Preventive Medicine*. The distinctions made by these scholars have been drawn on here to guide the research presented.

Research Methods

The Sample

The National Cancer Institute and the American Legacy Foundation provided funding to create a formal network of researchers involved with the science of tobacco harm reduction. For this study, the top researchers in tobacco-control research were invited to join the Tobacco Harm–Reduction Network. Those invited to participate constitute the sample utilized for this project.

A sampling frame of participants was identified through a key-word search of the NIH Computer Retrieval of Information on Scientific Projects (CRISP) and MedLine of the National Library of Medicine. Through these databases, 167 principal investigators, lead authors, or both were identified as potential

Table 1. Disciplines of Tobacco Harm–Reduction Network members

Disciplines	Fields included	Frequency
Chemistry/toxicology	Physical chemistry; organic chemistry; bio-organic chemistry; geo-organic chemistry; toxicology; biochemistry	12
Epidemiology	Epidemiology	4
Medicine/nursing/dentistry	Medicine; nursing; dentistry	8
Other behavioral	Behavioral sciences; health education; philosophy; communication research; English; public health; education	8
Other bench	Biophysics; physiology	2
Pharmacology	Pharmacology; psychopharmacology	4
Policy/law/ethics	Health policy; social policy; law	4
Psychology/psychiatry	Psychology; clinical psychology; experimental psychology; health psychology; physiologic psychology; social psychology	25

participants in the project. The invited participants for the actual study were drawn from the list using reputational sampling.[16] That is, a team of experts were employed to select from the list of 167 those who represented the most-accomplished researchers in their individual fields of inquiry, based on funding, publications, and general reputation in tobacco harm–reduction research. Thus, the sample is biased in favor of more-established researchers. A total of 68 potential network members were identified and sent a membership application in 2005, which included the questions used. No effort was made to select researchers by area of discipline.

It is important to note that while the Tobacco Harm–Reduction Network does have members in the formal sense of the term, consisting of the 68 top researchers selected for the study, the findings and analysis focus on the network of relationships established by these researchers on their own as they conducted their research. There was no formal meeting of the Tobacco Harm–Reduction Network prior to data collection, and members were asked only to report their past work-based interactions with each other.

Measures

The membership application requested information on the field of the highest earned degree, areas and extent of expertise, and the nature of relationships among the members and the products of those relationships. Of the 68 members identified, 67 returned the application (98.5% response rate).

Discipline was defined as the field in which the respondent earned his or her highest academic degree. Researchers were from a range of eight broadly defined disciplines identified by the authors, including psychology, medicine, policy, economics, pharmacy, epidemiology, other behavioral, and other bench. The distribution of disciplines within the sample is reported in Table 1.

Seventeen areas of expertise were identified a priori. Respondents were asked to indicate their level of expertise (*none or limited, some,* or *strong*) for each of the 17 categories identified by the authors. The frequencies and percent of Tobacco Harm–Reduction Network researchers who reported their expertise as *strong* in each area are reported in Table 2.

The membership application listed all 68 members of the broadly-defined network, and each was requested to indicate if he or she had had any previous work-related interaction with any other member. If the respondent answered *yes* to any interaction, she or he was asked about the nature of the interaction (*shared information, worked as part of a team without a formal arrangement,* or *worked as part of a team with a formal arrangement like a contract, memorandum of agreement, joint funding, or formal sharing of resources*).

Three additional items were asked about those with whom respondents had interactions: *Did the interaction help shape your thinking or your approach to your work?* (*yes* or *no*—the measure of interdisciplinarity); *Did the interaction lead to the production of a product, such as a journal article or research proposal?* (*yes* or *no*), and, if *yes, Does the product contain perspectives or elements that go beyond what you could have developed on your own?* (*yes* or *no*). These

Table 2. Frequencies and percent of Tobacco Harm–Reduction Network members reporting *strong* expertise in 17 tobacco harm–reduction content areas

Area of expertise	Frequency	%
Preclinical	13	19.4
Smoke chemistry	16	23.9
Smoking topography	20	29.9
Physiology	11	16.4
Addiction	35	52.2
Genetics	9	13.4
Clinical trials	12	17.9
Cessation	33	49.3
Adolescent smoking	21	31.3
Biomarkers	14	20.9
Advertising and promotions	9	13.4
Program evaluation	11	16.4
Tobacco industry	12	17.9
Population surveillance	14	20.9
Economics	4	6
Tobacco-control law	16	23.9
Ethics	9	13.4

Table 3. Items for indexes of multidisciplinary, interdisciplinary, and transdisciplinary relationships among Tobacco Harm–Reduction Network members

Item	Multidisciplinary relationship	Interdisciplinary relationship	Transdisciplinary relationship
Highest degree from different discipline	Yes	Yes	Yes
No interaction	Yes		
Shared information		Yes	Yes
Worked on team with or without contract		Yes	Yes
Resulted in a product			Yes
Product contained elements beyond what you could have developed on own			Yes

last two questions were both considered to be measures of transdisciplinarity, although because they were highly correlated (0.94), only the second one was used in the analysis. An overview is provided in Table 3. Multidisciplinary relationships occurred simply by virtue of having multiple disciplines represented in the Tobacco Harm–Reduction Network, regardless of whether or not interactions took place.

To increase the reliability of responses, network interactions were counted only if both parties in the relationship agreed that there was indeed a relationship. This confirmation procedure minimized the likelihood that results would be affected by respondents who claimed network relationships, when, in fact, such relationships did not actually exist. When there was a discrepancy about the exact type of relationship, a conservative approach was used, coding the data based on the least-formal type of tie mentioned by either party. However, more than 70% of all relationships were reported identically by both respondents. Data were also coded so that if one person reported a transdisciplinary tie but the other reported only an interdisciplinary tie, it was counted as interdisciplinary. Finally, because respondents were completing the survey as part of an application for membership in a network into which they had already been accepted, there was little incentive to inflate responses. Network relationships were then arrayed in a matrix form and analyzed using UCINET 6, the most commonly utilized network analysis software. Matrixes were subjected to data and variable quality tests to ensure the robustness of the data-collection practices and to minimize coding errors. Separate network matrices were constructed for interdisciplinary and transdisciplinary outcomes, although analytical efforts focused primarily on the transdisciplinary matrix. Networks were also displayed graphically using a network-visualization tool called NetDraw.

Results and Discussion

The overall network findings (Table 4) include a number of statistics indicating the network structure, or the relative positioning of actors within the network. The table reports statistics for both the interdisciplinary (no outcome) network and the transdisciplinary (a synergistic outcome) THR network.

Using the confirmed linking process described above, network density for any type of tie (interdisciplinary or multidisciplinary) was 0.326. Density refers to the connectivity of the full network. If every one of the 67 researchers responding to the questions was linked to every other researcher listed, the network would be completely connected. This would result in a network density score of 1.00. The finding that slightly less than one-third of total possible network connections were actually occurring may seem low to those unfamiliar with network analysis, but it actually indicates a well-connected network, especially because the network studied has so many members. Overall density breaks

Table 4. Comparative statistics for interdisciplinary (no outcome) and transdisciplinary (synergistic outcome) tobacco harm–reduction networks (n=67)

Network measure	Inter-disciplinary	Trans-disciplinary	Concept definition
Network density	32.56	7.10	Total actual number of connections as a percentage of total possible connections
Degree centrality	0–0.79	0–0.30	Range of number of individual connections (normalized)
Network betweenness	1.10	1.80	Extent to which actors mediate, or fall between, any other two actors on the shortest path between those actors
Network centralization index	0.06	0.18	The extent to which a network is centralized around one or a few actors
Fragmentation	0.36	0.68	The percentage of pairs of actors that are unreachable from each other
Inclusiveness	0.98	0.85	The percentage of actors connected to others

down to network-density scores of 0.226 for shared-information ties, 0.061 for working as part of a team with no formal arrangement like a contract, and 0.038 for working as part of a formal team with a contract or similar formal arrangement. Thus, the vast majority of ties involved relatively low-intensity interactions based on shared information.

Several measures of centrality are presented. The first, degree centrality, is simply the number of connections maintained by any individual in the network. Table 4 reports the range of these scores, normalized. It can be seen that the most central individual in the interdisciplinary network was more than 2.5 times as connected to others as the most central individual in the transdisciplinary network (0.79 vs 0.30). It is likely that this is because interdisciplinary ties are less intensive, allowing some individual researchers to develop a large number of relatively weak ties. Betweenness centrality provides a somewhat different measure of the degree to which individuals within the network are connected to other individuals. With betweenness, an individual is more central if he or she brokers the connection between two individuals along the shortest path (i.e., fewest links). Thus, unlike degree centrality, indirect ties are considered. When reported at the network level, the statistic represents the prevalence of betweenness centrality across all possible connections in the network. A higher number means that there are fewer direct routes between people, and thus brokerage is more essential to bridge across network members. The results indicated that individuals in transdisciplinary relationships were 61% (1.1/1.8) more likely to be on a brokered path linking any two other members of the network, indicative of the increased interdependency on specific actors to facilitate communication in sparser networks. The transdisciplinary ties were also more centralized (0.18 versus 0.06), meaning that they tended to cluster around fewer individuals, as opposed to interdisciplinary relationships, in which central actors were more dispersed across the full network. Consistent with these findings, the transdisciplinary network was also more fragmented and less inclusive.

A comparison of the multidisciplinary and the transdisciplinary networks can best be demonstrated by examining plots, or graphs, of the two networks (Figures 1 and 2). What is visually evident from these plots is that connectedness is much more widespread across the network when using interdisciplinary rather than transdisciplinary criteria, which is reflected statistically in the density scores of the two networks. Specifically, the transdisciplinary network density is only 0.071 versus 0.326 for the interdisciplinary network. Many more researchers are involved in network interactions that involve no product as an outcome, with many fewer involved in product-based interactions. This, of course, is to be expected, given the complexity and intensity of developing and maintaining transdisciplinary, synergy-based interactions.

What can also be seen from Figures 1 and 2 is that researchers from all disciplines are involved in both types of networks. However, especially with the transdisciplinary network, it can be seen that many of the interactions that result in a research product were not actually occurring across disciplines. For instance, although psychologists (solid blue square) are actively involved in the network (Figure 2), many of their interactions were with one another, rather than across disciplinary boundaries. Chemists (black triangles) engaged with one other in much the same way. Notably, there were few connections between chemists and psychologists, indicated by their relatively opposite positioning in the network map. Finally, the figures show that there is only one isolate (in policy—the grey box marked with +) in the interdisciplinary network, while in the transdisciplinary outcome-based network, there are ten isolates from a broad range of disciplines. Thus, fewer researchers are involved at all in these more complex, outcome-based relationships, which are difficult to build and maintain. Getting more of these isolates involved in transdisciplinary research would seem to be a highly desirable policy goal. Isolates are displayed in the left column of the figures and reflect those individual researchers who are not connected in any way to others within the network. This phenomenon is identified in Table 4 as inclusiveness.

To examine in greater depth the extent to which synergistic outcomes are occurring due to interactions across disciplines (i.e., transdisciplinarity), within-discipline network ties were analyzed versus across-discipline ties for both no outcome and synergistic outcomes. The findings (Table 5) indicate that what is known in the network literature as *homophily*, or the tendency to interact with people having similar backgrounds, is much more prevalent in some disciplines than others, at least regarding research on tobacco harm reduction.

The scores in Table 5 reflect the actual mean number of ties of each type maintained by researchers within each discipline. For instance, for the discipline labeled *medicine*, the mean number of ties to other medicine researchers was 2.13 for relationships where there was no outcome versus 11.2 mean connections (also no outcome) with Tobacco Harm–Reduction Network researchers outside the discipline of medicine (see also the red circles in the two figures). The actual numbers should be compared with the total number of respondents in that discipline. In the case of medicine, there were eight researchers, so the maximum number of ties to others in medicine could be seven (excludes ties to one's self). This compares with the potential number of transdisciplinary ties, which is quite large. Specifically, it is equal to the full size of the Tobacco Harm–Reduction Network (n=67) minus the total

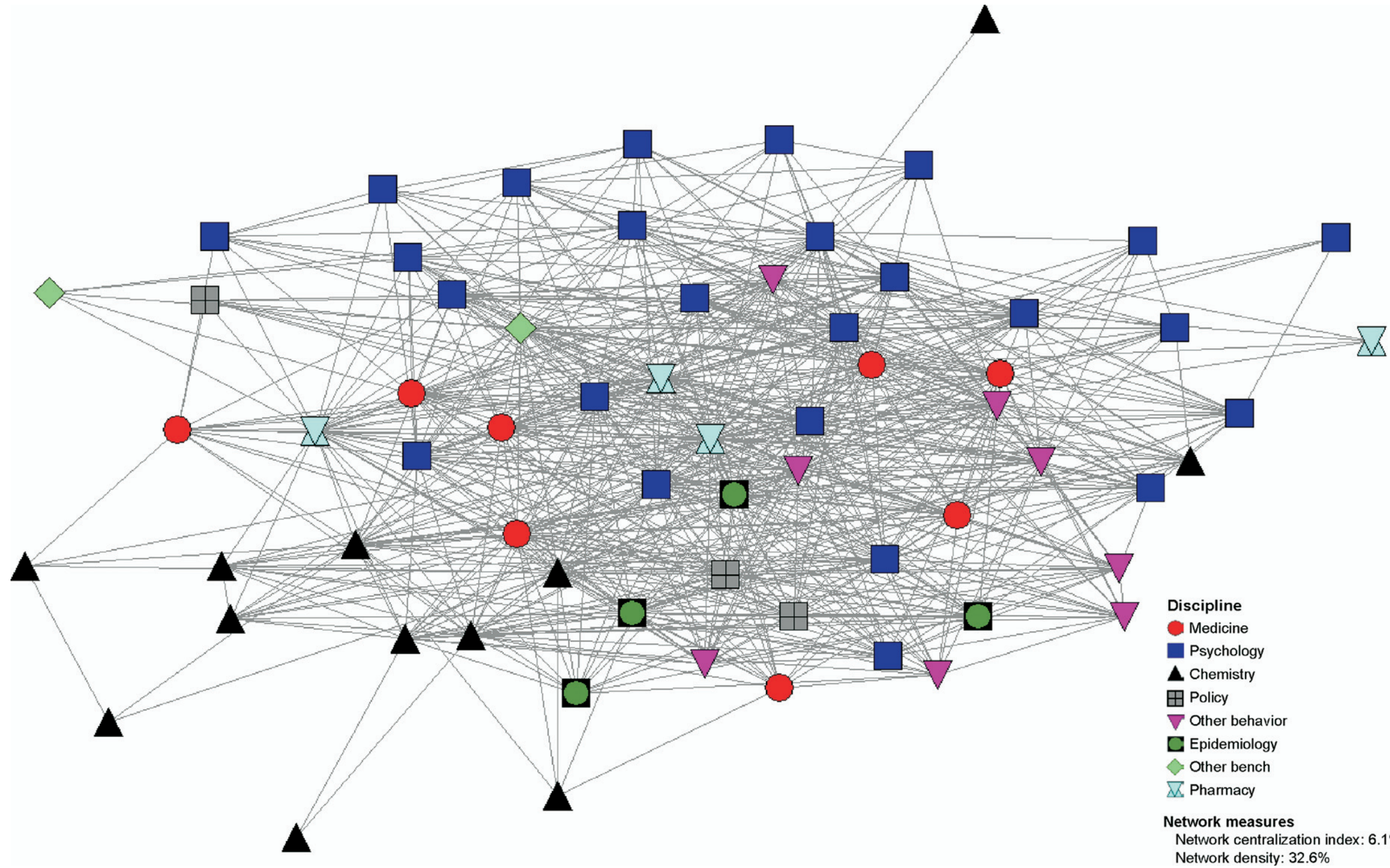


Figure 1. Plot of the Tobacco Harm–Reduction Network by discipline—any type of link, no outcome (interdisciplinarity)

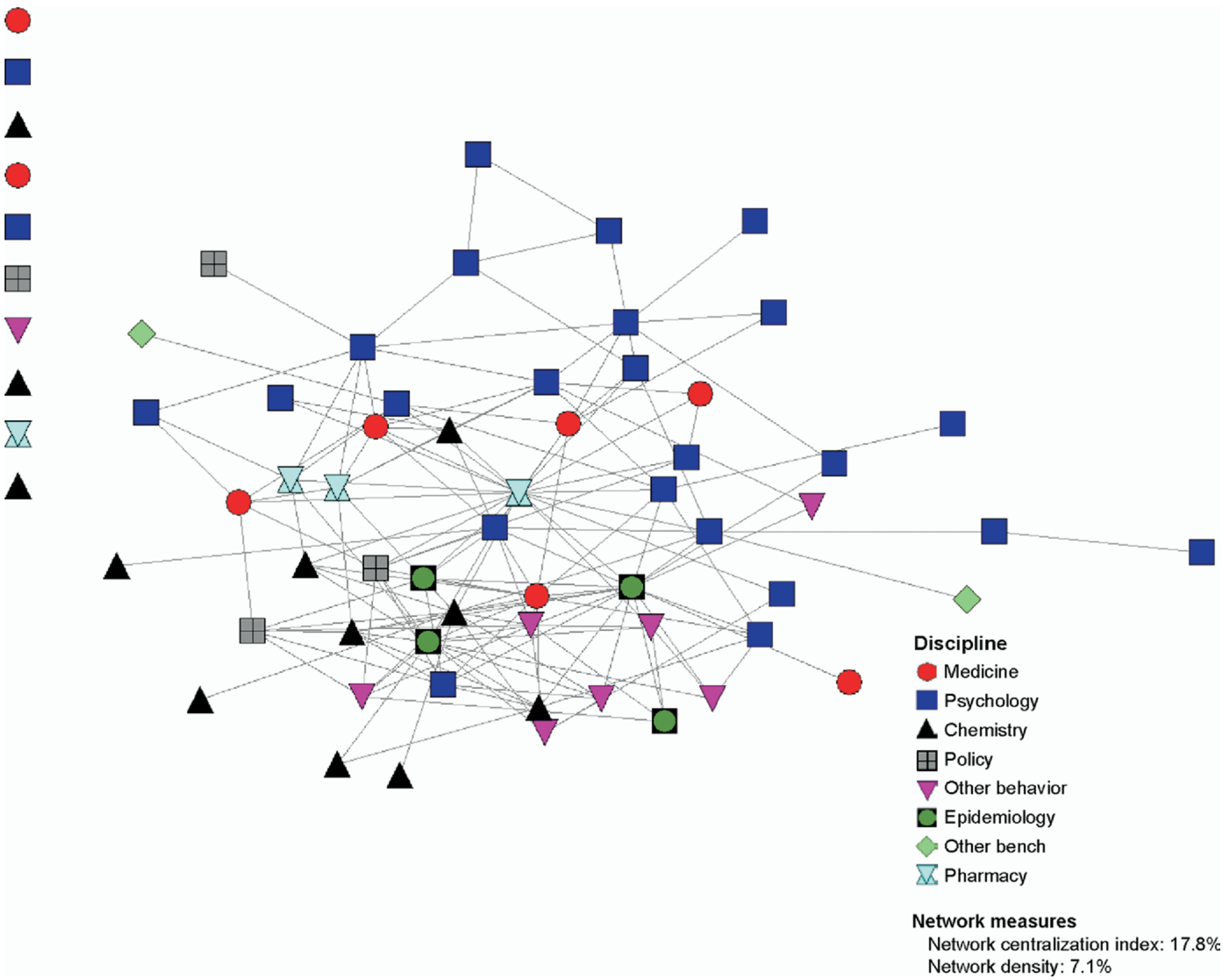


Figure 2. Plot of the Tobacco Harm–Reduction Network by discipline—any type of link, synergistic outcomes (transdisciplinarity)

number of respondents in a particular discipline (eight in medicine).

Not surprisingly, given the large numbers of out-of-discipline respondents, the findings indicate that there were always more ties across disciplines (heterophily) than within disciplines (homophily), regardless of whether or not there was a synergistic outcome. However, for both psychology and chemistry, the two largest groups, cross-disciplinary ties were only slightly greater than ties within the discipline. This suggests that these two groups of researchers tend to favor work among themselves more so than the other disciplinary groups studied. In contrast, for medicine, policy, pharmacology, and epidemiology, working across disciplines was much more commonplace.

Finally, Table 5 shows that although transdisciplinary ties with synergistic outcomes occurred far less frequently than did interdisciplinary ties with no outcomes, when synergistic outcomes did occur, they were far more likely to result from cross-disciplinary, heterophilous relationships than from homophilous ones. This was also true of no-outcome links, but to a much lesser extent. Specifically, the mean relationships per individual for interdisciplinary, no-outcome ties increased from 2.90 to 7.85 when ties were heterophilous, an increase of 271%. In contrast, mean relationships for transdisciplinary synergistic outcome ties increased from 0.34 to 1.82, a jump of 535%. Thus, for researchers seeking synergistic outcomes, there appears to be a substantial benefit to working with others outside their discipline rather than working solely within their discipline.

Conclusion

This is a first effort to examine, using network analytical techniques, how health researchers in tobacco control collaborate, and ultimately, how such collaborative

Table 5. Comparison of homophily versus heterophily: network ties across disciplines

Discipline	Interdisciplinary: no outcomes		Transdisciplinary: synergistic outcomes	
	Average number of connections to researchers in the same discipline (Homophily)	Average number of connections to researchers in other disciplines (Heterophily)	Average number of connections to researchers in the same discipline (Homophily)	Average number of connections to researchers in other disciplines (Heterophily)
Medicine (n=8)	2.13	11.20	0.00	2.19
Psychology (n=25)	5.00	5.72	0.84	1.16
Chemistry (n=12)	2.17	4.71	0.50	1.46
Policy (n=4)	0.25	7.38	0.00	2.00
Other behavioral (n=8)	1.88	10.30	0.63	1.69
Epidemiology (n=4)	1.25	12.60	0.50	5.00
Other bench (n=2)	0.50	8.50	0.00	0.50
Pharmacology (n=4)	1.00	14.12	0.25	3.88
Mean/individual	**2.90**	**7.85**	**0.34**	**1.82**

efforts produce transdisciplinary outcomes. The research has important implications for understanding the nature and extent of collaboration that occurs independent of any policy interventions. Based on findings from this initial mapping of the Tobacco Harm–Reduction Network, network researchers can readily see which types of cross-disciplinary collaborative efforts are most likely and which are most (and least) effective, from an outcome perspective. Health policymakers and funders can also draw on this information to provide incentives to researchers to collaborate more effectively, thereby resulting in transdisciplinary outcomes that can help advance the study of tobacco harm reduction.

Network analysis has been utilized in the past to examine relationships among health services organizations,[17,18] but not in previous work about health researchers.[15] The current study has shown that network analysis can be utilized to help understand, in a detailed way, both the extent and nature of collaborative relationships among individuals working within a particular health field, like tobacco control. Future research should build on what has been done in this study, possibly examining in greater detail the outcomes of transdisciplinary collaborations. In addition, longitudinal research efforts would demonstrate the shifting patterns of research from interdisciplinary ties to greater transdisciplinarity. Longitudinal research is especially appropriate for examining transdisciplinary relationships that are newly formed. Such relationships are likely to be cautious at first, then evolve toward greater involvement and more synergistic outcomes as trust builds and knowledge-sharing becomes more intensive.[18,19]

There are clear limitations to the work presented here. For one thing, it is unclear whether or not the results found are generalizable to other groups of health researchers. This study is exploratory and designed primarily to demonstrate the usefulness of network analysis for understanding cross-disciplinary engagements among researchers within a single health research field. Work on researchers in other fields is clearly called for, building on the methods and findings used in this study. Second, the issue of transdisciplinarity must be explored further, using more sophisticated methods. This study has operationalized both the outcomes and cross-disciplinarity of transdisciplinary research. However, it is clear that more detailed measures of outcomes could be assessed, and the issue of what actually constitutes a discipline might be refined. In particular, while the logic of transdisciplinarity is well-accepted, there has been little actual evidence that such relationships result in more or better outcomes than more traditional interdisciplinary work.

Third, the findings reported here are based on self-reports. A conservative approach of requiring confirmation of a tie by both partners was utilized, thereby enhancing the reliability of the interaction data. However, a more conservative approach would have been to examine actual working relationships as well, based on existing publication and grant data. Finally, it would be quite helpful to focus on transdisciplinary research networks in a more narrow way. Specifically, it would be useful to know if transdisciplinary relationships in various health fields occur across a full network of researchers or within more narrowly defined subnetworks, or cliques, consisting of, perhaps, no more than four or five researchers. It seems unreasonable to think that transdisciplinarity in any field should occur across a full network of scores of researchers rather than within more tightly specified clusters.

No financial disclosures were reported by the authors of this paper.

References

1. Best A, Tenkasi R, Trochim W, et al. Systemic transformational change in tobacco control: an overview of the Initiative for the Study and Implementation of Systems (ISIS). In: Casebeer AL, Harrison A, Mark AL, eds.

Innovations in health care: a reality check. New York: Palgrave MacMillan, 2006.
2. Leischow S, Best A, Trochim B, Clark P, Gallagher R, Marcus S. Systems thinking to improve the public's health. Am J Prev Med 2008; 35(2S):S196–S203.
3. Bozeman B, Corely E. Scientists' collaboration strategies: implications for scientific and technical human capital. Res Policy 2004;33:599–616.
4. National Cancer Institute. Greater than the sum: systems thinking in tobacco control. Tobacco Control Monograph No. 18. Bethesda MD: USDHHS, NIH, National Cancer Institute. NIH Pub. No. 06-6085, 2007. dccps.nci.nih.gov/TCRB/monographs/18/index.html.
5. Weick KE. Educational organizations as loosely coupled systems. Adm Sci Q 1976;21:1–19.
6. Kilduff M, Tsai W. Social networks and organizations. London: Sage Press, 2003.
7. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
8. Satterfield D, DeBruyn LM. The malignment of metaphor: silos revisited—repositories and sanctuaries for these times. Am J Prev Med 2005; 29:240–1.
9. Committee on Assessing Interactions Among Social, Behavioral, and Genetic Factors in Health. Hernandez LM, Blazer DG, eds. Genes, behavior, and the social environment: moving beyond the nature/nurture debate. Washington DC: The National Academies Press, 2006. www.nap.edu/catalog/11693.html.
10. National Cancer Institute. Transdisciplinary tobacco use research centers. 2004. cancercontrol.cancer.gov/tcrb/tturc/.
11. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
12. Monge PR, Contractor NS. Theories of communication networks. New York: Oxford University Press, 2003.
13. Stratton K, Shetty P, Wallace R, Bondurant S. Clearing the smoke: assessing the science base for tobacco harm reduction. Washington DC: National Academies Press, 2001.
14. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
15. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
16. Scott J. Social network analysis. Thousand Oaks CA. Sage, 2000.
17. Provan KG, Milward HB. A preliminary theory of interorganizational network effectiveness: a comparative study of four community mental health systems. Adm Sci Q 1995;40:1–33.
18. Provan KG, Nakama L, Veazie MA, Teufel-Shone NI, Huddleston C. Building community capacity around chronic disease services through a collaborative interorganizational network. Health Educ Behav 2003;30: 646–62.
19. Ring PS, Van de Ven AH. Developmental processes of cooperative inter-organizational relationships. Acad Manage Rev 1994;19:90–118.

Challenges for Multilevel Health Disparities Research in a Transdisciplinary Environment

John H. Holmes, PhD, Amy Lehman, MAS, Erinn Hade, MS, Amy K. Ferketich, PhD, Sarah Gehlert, PhD, Garth H. Rauscher, PhD, Judith Abrams, PhD, Chloe E. Bird, PhD

Abstract: Numerous factors play a part in health disparities. Although health disparities are manifested at the level of the individual, other contexts should be considered when investigating the associations of disparities with clinical outcomes. These contexts include families, neighborhoods, social organizations, and healthcare facilities. This paper reports on health disparities research as a multilevel research domain from the perspective of a large national initiative. The Centers for Population Health and Health Disparities (CPHHD) program was established by the NIH to examine the highly dimensional, complex nature of disparities and their effects on health. Because of its inherently transdisciplinary nature, the CPHHD program provides a unique environment in which to perform multilevel health disparities research. During the course of the program, the CPHHD centers have experienced challenges specific to this type of research. The challenges were categorized along three axes: sources of subjects and data, data characteristics, and multilevel analysis and interpretation. The CPHHDs collectively offer a unique example of how these challenges are met; just as importantly, they reveal a broad range of issues that health disparities researchers should consider as they pursue transdisciplinary investigations in this domain, particularly in the context of a large team science initiative.

(Am J Prev Med 2008;35(2S):S182–S192)

Introduction and Rationale

It has been well-established that racial and ethnic minorities and individuals with fewer economic resources suffer a disproportionate burden of illness and death in the U.S. Such health disparities have been documented in many diseases and conditions, including cardiovascular disease,[1,2] cancer,[3] HIV/AIDS,[4] and infant mortality.[5] Additionally, racial and socioeconomic disparities have been observed for health behaviors, such as cancer screening[6,7] and smoking.[8–10]

Although gaps have narrowed over time for some health behaviors, many have not. Moreover, health services research indicates that even where disparities in processes of care (e.g., screening) have been addressed, disparities in general, as well as gaps in intermediate outcomes (e.g., achieving control of blood sugar,[11] blood pressure,[12] and cholesterol[13]), persist. However, a recent survey of Medicare recipients found that self-reports failed to identify racial/ethnic disparities in mammography screening that were apparent from claims data.[14] This, in combination with a recent meta-analysis of the inaccuracy of cancer screening self-reports,[15] suggests that significant disparities in cancer-screening prevalence in the U.S. are being masked by differential over-reporting. Despite these biases, the problem of health disparities is so great that the USDHHS has made the elimination of disparities in health and health care one of the two major objectives of *Healthy People 2010*.[16]

Trends in Health Disparities

In some instances, disparities in health by race/ethnicity and SES have been increasing over the past decade.[17] Silva et al.[18] reported findings on changes in both black–white and low–high income disparities over time for 22 select causes of death, communicable diseases, and birth outcomes in Chicago between 1979–1981 and 1996–1998. The authors reported that for 19 of the 22 causes, the black–white rate ratio significantly increased over time, suggesting that racial disparities have increased over the 18-year period. Similarly, for 14 of the

From the Department of Biostatistics and Epidemiology, University of Pennsylvania School of Medicine (Holmes), Philadelphia, Pennsylvania; the Center for Biostatistics (Lehman, Hade), The Ohio State University, and the Division of Epidemiology, The Ohio State University College of Public Health (Ferketich), Columbus, Ohio; the School of Social Service Administration (Ferketich), University of Chicago, and the School of Public Health, University of Illinois at Chicago (Rauscher), Chicago, Illinois; The Center for Urban and African American Health, Wayne State University (Abrams), Detroit, Michigan; and the RAND Corporation (Bird), Santa Monica, California

Address correspondence and reprint requests to: John H. Holmes, PhD, Center for Clinical Epidemiology and Biostatistics, University of Pennsylvania School of Medicine, 726 Blockley Hall, 423 Guardian Drive, Philadelphia PA 19104. E-mail: jhholmes@mail.med.upenn.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.019

16 measures included in the low–high income disparities analysis, the rate ratio increased between 1979–1981 and 1996–1998.

Starting around 1980, different trends in coronary heart disease (CHD) mortality have been observed for black and white men and women.[19–21] Since 1980, the rate of CHD mortality has declined more rapidly among white men compared to black men in the U.S. While a similar pattern has emerged among women, more striking is the observation that the trend lines crossed in the mid-1980s, and now black women have higher death rates than white women. These and other studies of health disparity make it clear that progress toward reducing health disparities in the U.S. is, at best, much slower than hoped, and in many cases disparities have increased rather than decreased.

Traditional etiologic approaches to studying disparities have often been limited in scope with respect to data-collection and analysis strategies, leaving researchers to draw conclusions that are consistent with their data but sometimes require large inferential leaps. For example, many studies have found that census-tract SES explains much of the black–white disparity in breast cancer stage at diagnosis.[22] While these studies suggest that disparities are largely driven by social factors, they say little about the exact proximal or distal causes of the disparity. Conclusions about the causes of disparity that are drawn from such studies are potentially and justifiably open to criticism.[23] For example, individual-level health behaviors may or may not be influenced by environmental factors that may be bundled with SES; in a real sense, SES proxies these other factors without providing any real information about them. In their work on transdisciplinary approaches to the etiology of cancer, Hiatt and Breen[24] note the importance of environmental and socioeconomic factors as part of the web of causation, specifically at the level of social determinants; these factors include characteristics of the built environment. Whereas their model was developed from a focus on cancer, it is applicable to many other health outcomes such as heart disease, hypertension, and diabetes, all of which may be mediated by broadly defined social determinants. Focusing on such characteristics as census tract-specific SES as a sole predictor of such outcomes ignores the influence of more specific and potentially more informative variables such as the neighborhood availability of sidewalks, grocery stores, and recreational facilities.

A Multilevel Approach to Studying Health Disparities

A growing body of research demonstrates that health disparities constitute a highly complex problem domain that both exists and operates on many different levels.[25–32] In other words, many disparities that affect an individual's opportunity to pursue a healthy life occur above and beyond individual-level characteristics, resources, and behaviors. One example is residential environment: An individual living in a high-risk or resource-poor environment may acquire over time a biological disadvantage relative to someone with similar personal characteristics living in a more salutary environment.[33] This example suggests only one of many ways in which health disparities may be attributable to a wide range of contextual factors operating beyond the individual level.

Advantages of Multilevel Research in Studying Health Disparities

There are several reasons for applying the concepts and tools of multilevel research to health disparities. First, only multilevel research can examine the effects of one factor at one level (e.g., personal behaviors) while controlling for potential confounding at another level (e.g., neighborhood differences), or examine the interactions among factors situated at different levels. An example of such an interaction is seen in the effect of social isolation on the expression of genes in breast cancer.[34] This potentially complex interaction had previously been identified as a limitation of disparities research, requiring that the researcher assume that an effect is not confounded by a factor at another level of analysis. Only multilevel research can examine how individual behaviors that influence risk for disease are themselves influenced by larger societal factors such as access to quality health care, social networks, and neighborhood resources. Larger societal factors, such as poverty, can also influence the risk of disease through mechanisms other than health behaviors. Social isolation is higher in neighborhoods with outdated infrastructure, characterized by such features as poorly maintained and inadequate utility systems, the lack of availability of services and commerce, and the inadequate ability of public safety agencies to respond to emergencies.[35] Understanding the interplay among etiologic factors situated at different levels of analysis will enable interventions to be targeted with greater precision, thus better ensuring their success.

Multilevel studies are not easy to undertake; they require a comprehensive conceptual model of etiologic factors that are distributed across multiple levels, data collection from multiple sources, and appropriate statistical models to account for the relationships among various levels of analysis. With this in mind, NIH recently funded eight Centers for Population Health and Health Disparities (CPHHDs) whose mission is to foster and conduct transdisciplinary health disparities research across multiple levels, pathways, or contexts. This paper highlights some of the key lessons learned through the authors' transdisciplinary collaborations within and among centers. First described is the conceptual model that forms the basis for the CPHHD initiative; then specific examples from the various CPHHD centers are provided to highlight the special issues and challenges encountered in multilevel statistical analyses. Finally, the authors' experience in the CPHHD is summarized, and suggestions for future directions in evaluating transdisciplinary research are presented.

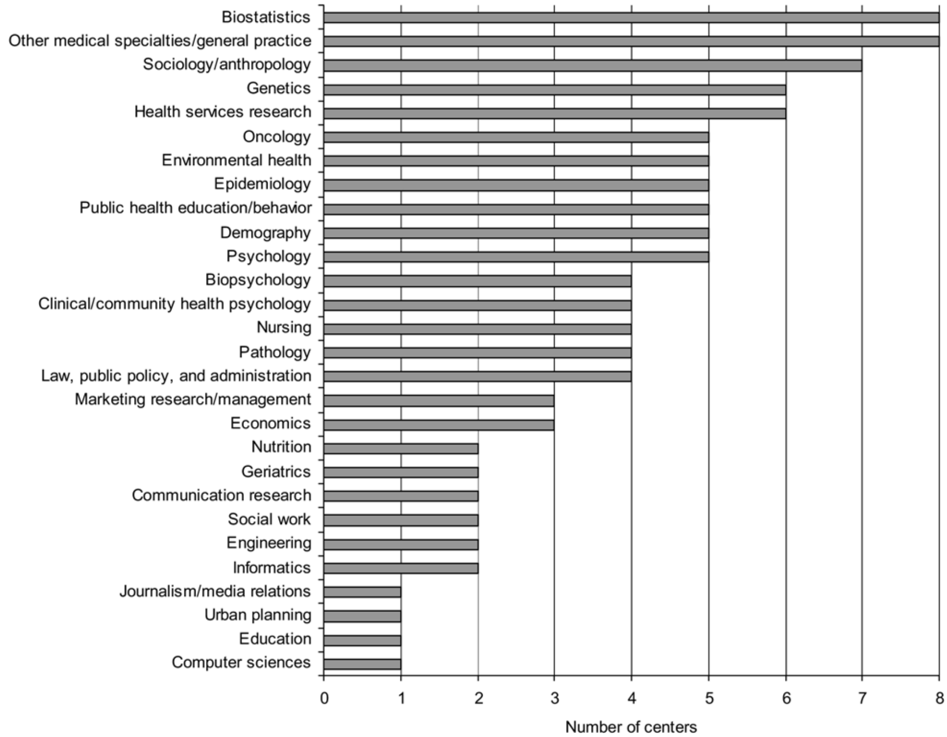


Figure 1. Disciplines represented across the CPHHDs, ranked by prevalence

The Centers for Population Health and Health Disparities

In September 2003, the NIH established the eight CPHHDs to conduct cutting-edge research to understand and reduce differences in health outcomes, access, and care: the ways the social and physical environment, behavioral factors, and biologic pathways interact to determine health and disease in populations. The centers include the University of Illinois at Chicago, the University of Chicago, Tufts and Northeastern universities, the RAND Corporation, the University of Texas Medical Branch, The Ohio State University, Wayne State University, and the University of Pennsylvania. Projects at the centers focus variously on obesity, cardiovascular disease, breast cancer, prostate cancer, cervical cancer, mental health, gene–environment interactions, psychosocial stress, and other factors affecting low-income whites, African Americans, Hispanics, and the elderly.

The CPHHDs As a Laboratory for Transdisciplinary Research

Before examining the transdisciplinarity of the CPHHDs, it is important to consider the distinctions among multidisciplinary, interdisciplinary, and transdisciplinary research. In multidisciplinary research, scientists from different fields work independently but bring their expertise to solve a problem that is addressed through a mosaic of activity; each scientist represents and acts only within his or her own domain. Interdisciplinary research requires more integration of multiple scientific perspectives, but researchers retain their discipline-specific grounding. Transdisciplinary research differs from these in that scientists not only collaborate and integrate their respective discipline-specific expertise, but do so within the context of a new, common conceptual framework that transcends the frameworks used within their respective disciplines.[36,37]

The CPHHDs are intrinsically multidisciplinary in that many disciplines are represented within and across them, as illustrated in Figure 1. Specifically, the eight CPHHDs together represent 42 disciplines, which can be grouped into biological and clinical sciences; media and communications; public health, policy, and planning; social and behavioral sciences; and biomechanics/statistics.[38]

While Figure 1 reveals that many different disciplines are represented in the CPHHD program, it does not show how these disciplines are spread across the centers, nor does it suggest the interdisciplinary nature of the CPHHD. In fact, the individual centers and the CPHHD initiative as a whole are highly interdisciplinary, in that many different disciplines are represented on each component project at each center. Furthermore, these projects typically require considerable collaboration and a degree of integration. Table 1 shows the various disciplines involved in the CPHHD initiative grouped by center, and represents the opportunities for horizontal and vertical integration that are critical to transdisciplinary research.[39,40]

The CPHHD initiative fosters both vertical-integration dimensions in supporting collaborative, integrative health disparities research at the centers as well as horizontal collaboration and integration across the centers. This suggests that the CPHHD initiative is not only interdisciplinary but transdisciplinary as well, but transdisciplinarity can be an elusive characteristic to measure.[37,39]

Table 1. The disciplines of the CPHHDs

	UIC	Chicago	OSU	Penn	UTMB	WSU	Tufts	RAND
Biological sciences								
Biopsychology	X	X	X				X	
Genetics	X	X	X	X		X	X	
Nutrition						X	X	
Oncology	X	X	X	X		X		
Clinical sciences								
Clinical/community/health psychology			X	X	X		X	
Geriatrics					X		X	
Nursing	X		X		X	X		
Pathology	X	X			X	X		
Other medical specialties, general practice	X	X	X	X	X	X	X	X
Media and communications								
Communication research			X	X				
Journalism/media relations								X
Marketing research/management			X		X			X
Public health, policy, and planning								
Environmental health			X		X	X	X	X
Epidemiology	X	X	X	X		X		X
Health services research	X		X	X	X		X	X
Law, public policy, and administration	X		X	X				X
Public health education/behavior			X	X	X	X		X
Urban planning	X							
Social and behavioral sciences								
Demography	X				X	X	X	X
Economics			X		X			X
Education					X			
Psychology[a]	X	X	X			X	X	
Sociology/anthropology	X			X	X	X	X	X
Social work	X	X						
Biomechanics/statistics								
Biostatistics	X	X	X	X	X	X	X	X
Computer sciences				X				
Engineering				X				X
Informatics		X		X				

[a]Includes cognitive, developmental, educational, and social psychology
CPHHDs, Centers for Population Health and Health Disparities; Chicago, University of Chicago; OSU, The Ohio State University; Penn, University of Pennsylvania; RAND, the RAND Corporation; Tufts, Tufts and Northeastern universities; UIC, University of Illinois at Chicago; UTMB, University of Texas Medical Branch; WSU, Wayne State University

To capture evidence of collaboration and the emergence of transdisciplinary research, the CPHHD evaluation working group conducts an annual survey of the investigators at each center. The conceptual model shown in Figure 2 was used both to develop the survey instrument and as a guide for evaluating the CPHHD program as a whole. In this model, a temporal series of transdisciplinary processes are grouped as immediate markers, intermediate markers, short-term outcomes, and long-term outcomes. (The CPHHD model is similar to the antecedent–process–outcome model proposed by Stokols et al.[37]) The responses to the survey were coded, using the specific markers and outcomes represented in the boxes. For example, *transdisciplinary integration* would be evidenced by the integration of methods, models, and findings from at least two disciplines. To this end, the surveys focused on five domains of transdisciplinary science. Evidence of (1) collaboration was seen in the participation of schools, healthcare institutions, and community organizations; of (2) capacity building in new seminars and conference series, and increased institutional commitment to infrastructure and other support; of (3) integration in the development of new, multipurpose databases; common conceptual language pertaining to health disparities; and new analytic methods; of (4) knowledge in the emergence of new lines of inquiry; multicenter and transdisciplinary manuscripts (such as this one); and new grant applications; and of (5) innovation in the development of new instruments and analytic methods. In addition to the annual survey, progress toward transdisciplinarity was assessed using social-network analysis.[41] Investigators and researchers at each center participated in a self-administered survey aimed at identifying collaborators and their disciplines. The social-network data are currently being analyzed.

There is substantial evidence of the emergence of a new, transdisciplinary science of health disparities research across the CPHHD program. The CPHHDs face a number of challenges to achieving transdisciplinary functioning, such as developing a shared lexicon, pooling the best of disciplinary theories, deciding upon a

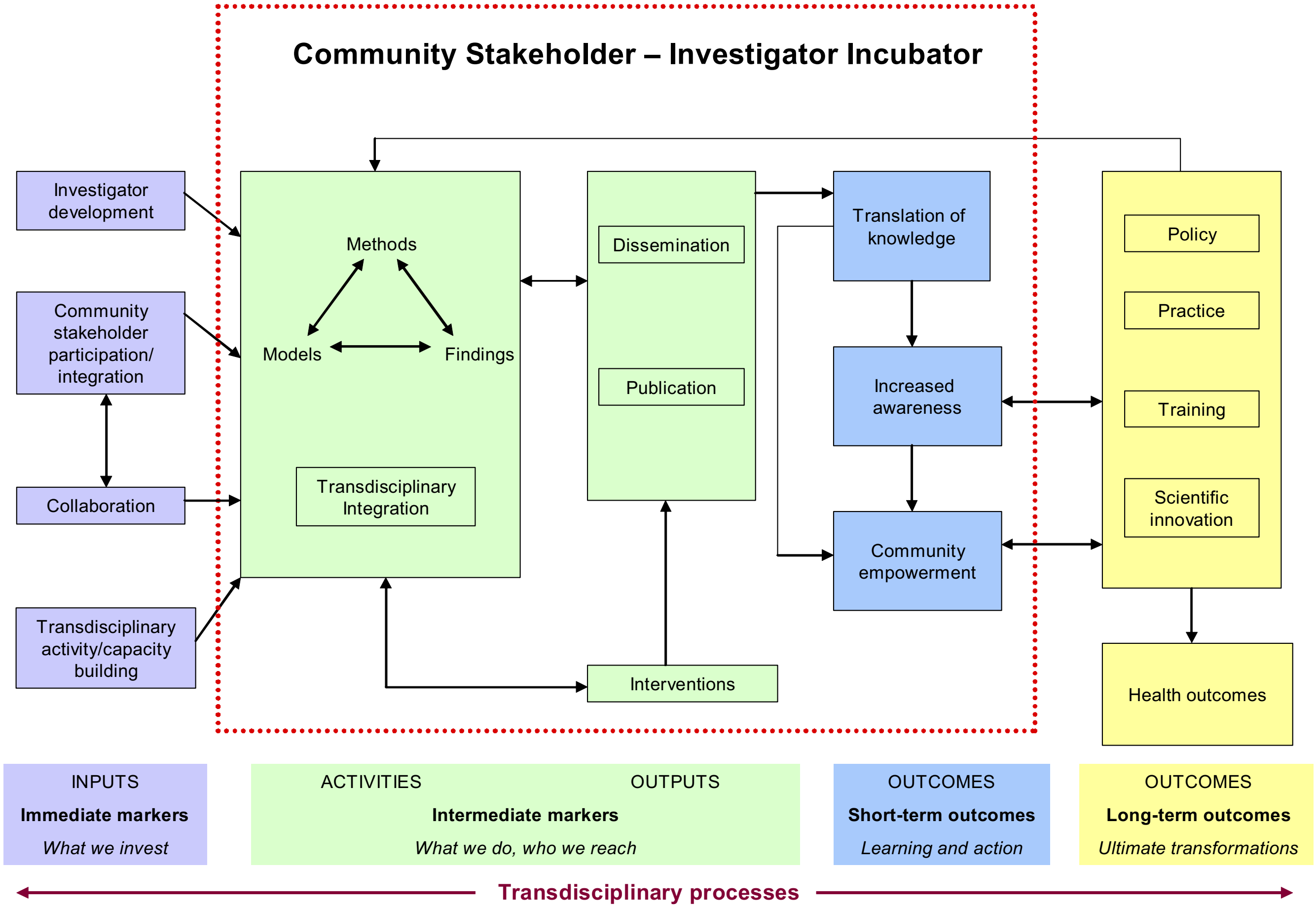


Figure 2. The logic model for the CPHHDs

shared research design or designs, and determining the best methods for analyzing data. Nevertheless, multilevel analysis distinguishes itself among these significant challenges, and in a mid-course survey conducted in 2006, CPHHD investigators listed multilevel analysis as the single greatest challenge facing their centers. One reason for this is that multilevel research demands a level of interaction that is much greater than is characteristic of monodisciplinary or traditional multidisciplinary collaboration. In the multilevel research discussed in this paper, clinicians, social scientists, informaticians, statisticians, and health communication experts have worked together in highly evolved teams that address facets of health disparities issues that are out of their normal disciplinary sphere. Accordingly, the authors found that multilevel research provides an extraordinary domain for transdisciplinary research, in that investigators form and participate in highly collaborative, integrative relationships that transcend their own disciplines. In addition, through its focus on linking science, training, and application to public health practice and policy, the CPHHD initiative provides a unique environment for multilevel health disparities research—one that connects the scientific discovery and training phases of team science with the translational, health-improvement goals of transdisciplinary action research.[40]

Challenges and Solutions of Multilevel Analysis and the CPHHDs

The following section outlines shared challenges to performing multilevel analyses across the CPHHD program and the solutions that have been developed to address them. Most of these challenges parallel the issues raised in the introduction to this supplement, including the need for conceptual frameworks, methodologic and analytic issues, and translational initiatives. The focus here is on the first two sets of issues, grouping specific challenges along three conceptual axes: sources of subjects and data, data characteristics, and multilevel analysis and interpretation.

Sources of Subjects and Data

Challenge: the number of sites (clusters) for study. An unusually large or small number of sites (clusters) from which participants are recruited may affect a statistical analysis. For example, the original Ohio State University CPHHD analysis plan was to use a survey approach to account for interclass correlation among subjects at the same clinic. However, computational issues resulting from the small number of clinics (N=14) prevented investigators from developing models with adequate numbers of covariates. The current analysis strategy is to fit mixed models (i.e., hierarchical linear models) that incorporate the site as a random effect rather than survey-based models.

Challenge: a limited number of observations per cluster. The University of Illinois at Chicago is examining the hypothesis that the racial and ethnic disparities in stage at diagnosis and treatment for breast cancer can be explained in part by differences in healthcare facilities. Random-intercept models will be used to account for the clustering of patients within facilities. The roughly 900 patients in the study are distributed across more than 60 facilities in Chicago that detect, diagnose, and treat breast cancer, and many facilities have only one patient associated with them. For example, there are more than 40 breast-surgery facilities with only one affiliated patient in the study. Because clusters with a single observation contribute only to the estimation of between-level parameters and not to within-level parameters, the variation associated with smaller facilities (i.e., cluster size=1) would be missed. One solution to this problem would be to group facilities when cluster size=1 into a smaller number of clusters with common attributes (e.g., facility type, location) so that most or all clusters would have a sample size >1.

Challenge: incorporating census information. Analyses across CPHHDs will almost certainly incorporate census information at some point. Decisions, therefore, must be made about how to define variables appropriately, to deal effectively with sparse populations in census regions, and to geocode participants' addresses. The Ohio State University CPHHD recruits patients from clinics in 14 counties in Appalachian Ohio. In order to geocode the location of each participant, interviewers were given a hand-held device which measured the latitude and longitude at the site of the interview. The data were then used to determine the census tract for each participant. Because of the rural locations as well as issues with the devices, it has been difficult to assign the proper census tract for some of the observations based on the device data. The investigators have been able to determine the census tracts for some of the participants by entering the street address in the Census Bureau's website. They are currently working to resolve the few cases where the calculated tract and the tract from the Census Bureau's website do not agree.

A challenge faced by the University of Illinois at Chicago CPHHD is how to obtain the best imputation of patient SES using census data derived at the level of the census tract. Census-data associations with disease represent a mixture of area-level and individual-level effects. In order to impute patient-level SES as accurately as possible, this CPHHD stratified census-tract information into nine separate cross-classifications of age and race. They then assigned census tract–, age-, and race-specific estimates for the percentage below the federal poverty level to each individual accordingly, and used these estimates as imputations of individual-level poverty status. An alternative and more traditional approach is to assign the mean poverty level in a census tract to all patients residing in that tract without regard to other patient attributes. The investigators here found that the former approach resulted in more parsimonious models than the latter. When poverty status was assigned solely based on patient census tract, models of poverty and race in predicting stage at breast-cancer diagnosis contained nonlinear effects, and race and poverty interacted. On the other hand, when poverty status was assigned based on patient census tract, age, and race, all effects were linear, and the final model did not contain any interactions among age, race, and census tract. Because of the availability of common demographic variables such as age and race, this approach could be generalized to other settings where researchers need to develop a poverty-status indicator.

Another problem was encountered when imputing poverty status from census data. Estimates of poverty within census age–race groups are often based on sparse data, and therefore are less precise and more likely to be biased. One possible solution to this problem is to use an empirical Bayes approach to model estimates in a manner that would shrink unstable estimates toward the overall census tract mean, with the extent of shrinkage depending on how sparse the stratum-specific data are relative to the data for that census tract. University of Illinois at Chicago investigators found that using empirical Bayes to estimate poverty within census age–race groups provided no advantage over using more traditional (and simpler) estimation methods, and the results were similar in both cases. This finding made sense, given that sparsely populated census age–race strata would tend to contribute little to the overall association between poverty and stage at diagnosis.

The RAND project examining data from the third national health and nutrition examination survey (NHANES III) focuses on the socioeconomic environment, the socio-structural environment, and the quality of neighborhoods. Many contextual variables were derived from the U.S. Census 1990 and 2000 data (interpolating for intercensal years and extrapolating from 2000 forward); neighborhood characteristics were measured at the census-tract level. To link the geographic- and individual-level data, study participants' residential addresses required geocoding, which in turn necessitated a decision about the level of geocoding to be performed (e.g., ZIP code, census tract, or block group). Other considerations included determining which geocoded measures of physical and social characteristics of neighborhoods were most relevant to individual health, and whether the potential effects of continuously measured neighborhood characteristics were likely to manifest themselves across a continuum or emerge at some threshold level. The RAND project focused on the effects of environments at the most immediate level of living—the neighborhood. Environment at the census tract was first considered, to ensure homogenous populations and smaller spatial areas. However, the characteristics of larger administrative units (e.g., county or metropolitan statistical area) were also considered, to investigate whether larger economic considerations (e.g., job availability, unemployment, levels of inequality within regions) may play a role in outcomes.

Challenge: using existing data from other research studies. Health disparities research often incorporates existing data from studies that were not designed to collect multilevel data. These data present special challenges for researchers wishing to use multilevel analysis. In particular, CPHHD researchers have encountered challenges using existing-survey data as well as clinical-trials data.

Working with existing survey data typically does not allow researchers to consider examining self-defined neighborhood levels. This limitation is both advantageous and disadvantageous; for example, individuals may infrequent contact with areas of their census tract that drive many of the average characteristics of the entire census tract. However, the existence of objective data avoids the problems of reverse causality whereby individuals with poorer health may report more negatively on their residential environment, either because of differences in their perceptions of the environment (e.g., reporting more or less disorder or disadvantage) or because of their experience of the environment (e.g., greater difficulty with poor air quality).

As with many large sample surveys, NHANES III data are not limited to questionnaire items, but include physical exam and biomarker information as well. With the addition of census data, multilevel models could explore potential interactions that may arise from social-determinants-of-health outcome etiology; among others, these include whether the impact of neighborhood SES and built-environment characteristics varies with individual SES, how it varies, and whether such interactions help to explain health disparities.[24] For example, do the effects of neighborhood SES on specific health behaviors vary by gender or race/ethnicity?

Other types of studies offer the potential for multilevel research, but pose challenges as well. For example, the RAND CPHHD is developing multilevel models using observational and clinical-trial data from the women's health initiative. These data pose a particular challenge in that there is clustering at the level of "medical center." In addition, some metropolitan statistical areas may have several medical centers, while participants may be enrolled in a center that serves several metropolitan statistical areas. Investigators at the University of Pennsylvania are using data from an existing case–control study to investigate the possible interactions of neighborhood characteristics with genes and screening behaviors in explaining racial differences in prostate cancer outcomes.

Challenge: accessing detailed neighborhood-characteristics data. Census data do not provide researchers with detailed neighborhood characteristics that could be useful in multilevel health disparities analysis. For example, property-specific or parcel-specific data are not available through the census. Researchers seeking to use property size, value, or length of ownership as possible covariates or predictors in multilevel models need to identify other sources of these characteristics. Two CPHHDs have identified local neighborhood characteristics data, but these sources are not without their challenges. The University of Pennsylvania CPHHD has a resource on campus, the Cartographic Modeling Laboratory, that provides access to detailed neighborhood data. However, the data are restricted to Philadelphia, and the use of some data requires special approval from city agencies. Similarly, the University of Chicago CPHHD has access to data from the Chicago Area Study,[42] but it is unique to the city of Chicago, was collected more than a decade ago, and may not represent the current characteristics of neighborhoods that have undergone gentrification or other demographic changes since then.

The Ohio State University CPHHD had a slightly different experience with this challenge. Early in the planning stages of the projects, researchers needed a list of all providers (in clinics, health departments, and other healthcare facilities) that performed Pap screening in their 14 Appalachian counties. Because there was no resource that could easily provide this inventory, the investigators had to work with local agencies, key informants, and local field staff to develop a list of providers, using a snowball-sampling approach.

Challenge: issues in recruiting from special populations that affect multilevel analysis. The Ohio State University CPHHD recruits patients from clinics in 14 counties in Appalachian Ohio. Researchers there have experienced challenges in patient sampling (e.g., it is inconsistent across clinics; patient lists are difficult and time-consuming to obtain); in rates of response among these populations (e.g., how to extrapolate to all of Appalachian Ohio); and in interview and follow-up burden due to travel difficulties, contact challenges, and lack of incentives. The potential effects of these issues on outcomes will be explored during the analysis phase, and their impact on the interpretation of results will be carefully considered.

The CPHHD at Tufts/Northeastern universities recruits Puerto Rican adults from the Boston area. Although a growing population, they constitute less than 10% of households in the city. Further, the presence of Puerto Ricans is identified by the census only at the tract level. At the block level, there may be many Hispanic individuals, but none who are Puerto Rican. Sampling proceeded by identifying tracts that contain at least ten Puerto Ricans, and then moving to the block level, with door-to door enumeration of blocks that, according to the census, contain at least four Hispanics. To use lower cutoff points would be prohibitive in cost, but as the study is designed, many blocks are enumerated with no Puerto Ricans identified.

This has several consequences, because Puerto Ricans at lower SES levels are most likely to live in more-concentrated communities. First, the sample will not include Puerto Ricans with higher-level SES who live in more-integrated environments; second, SES distribution is therefore truncated, resulting in lower variability across sampled neighborhoods. This results in limitations in generalizability to those Puerto Ricans living in neighborhoods with other Hispanics, and limits power for multilevel analyses.

To improve this, these researchers have included participants who are recruited from community gatherings, such as Puerto Rican festivals. This method does identify individuals who live in less Hispanic-dense neighborhoods (although they remain underrepresented), but it may complicate analyses. One such complication is the lack of homogeneity within the study sample. Community gatherings may draw people from outside the neighborhood under study. In addition, the people who attend such gatherings may be nonrepresentative of the neighborhood as a whole, even if they live in that neighborhood.

Characteristics of Data for Multilevel Research

Challenge: dealing with significantly inter-correlated variables. Every CPHHD considers both SES and race/ethnicity, which are highly correlated, in analyses. A number of solutions have been devised to address this conundrum. Researchers at the University of Illinois at Chicago CPHHD undertook a secondary data analysis, linking data on breast cancer stage at diagnosis from the Illinois State Cancer Registry for the years 1994–2000 with census data for Chicago. Their initial plan was to limit the geographic region to Chicago. They initially encountered a high correlation between census-tract SES and census-tract composition by race/ethnicity within the city limits. This made it virtually impossible to tease apart the separate effects of SES and race/ethnicity on stage at diagnosis. As a solution to the problem, the group expanded the geographic region of interest to include all of Cook County, in which there are suburbs with substantial numbers of relatively affluent minority populations.

The RAND CPHHD addressed the issue by examining the distribution of each race/ethnicity on its measure of neighborhood SES to determine the degree of overlap. They determined that there was insufficient overlap to ensure that neighborhood SES effects occur for all groups by race/ethnicity, and they are conducting stratified analyses by race/ethnicity in order to test for effects based on the actual range of the data within each subgroup. Similarly, RAND CPHHD investigators have found that, although men and women are not differentially distributed across census tracts (because neighborhoods are not gender-segregated), there are myriad gender differences in contextual effects that necessitate the use of either multiple interaction terms or, in some cases, gender-stratified models in order to capture the differential effects of specific aspects of neighborhood contexts on men compared to women.

Challenge: justifying community- and neighborhood-level data from two sites that were conceptualized and gathered in different ways. The University of Chicago CPHHD originally planned to work only on the South Side of Chicago. Thus, all neighborhood and community data were from the same sources (e.g., the city of Chicago). Then the group began to work in Gary, Indiana, in order to increase sample size. That posed a problem, because the data had been gathered by another source and were not completely comparable to the Chicago data. The approach to this challenge was to explore how each respective source defined each variable that was measured (e.g., violent crime or safety of housing) and to find the lowest common denominator among measures across sources.

Challenge: making the most of administrative data to examine contextual effects. In some cases, tract-level data fail to capture important aspects of residential exposure—for example, because otherwise-similar tracts are surrounded by differing concentrations of poverty or by built environments of varying quality. A solution developed by RAND and University of Chicago investigators was to examine a combination of census-tract characteristics and the characteristics of a buffer area around each tract. In additional work, the RAND CPHHD has begun to use GIS-based measures to capture distance and exposure—for example, to alcohol outlets.[43] Because businesses are often in separate areas that are not zoned for housing and thus are not classified as census tracts, measuring exposure to alcohol outlets only in tracts (or in grocery stores or fast-food outlets) results in a systematic undercount of residents' exposure to these businesses. In other projects, RAND investigators have employed similar models to capture distance from parks and other green space.[44]

Analyzing Multilevel Data and Interpreting the Results

Transdisciplinary research requires collaborative and integrative thinking. Multilevel analysis provides a natural environment for this in that it requires substantial input from experts in a variety of content and methodologic domains. Effective collaboration in multilevel research is facilitated to the extent that team members share an interdisciplinary or transdisciplinary research orientation from the outset of the project. Yet the progression from multidisciplinary to transdisciplinary collaboration in the context of multilevel, multisite team initiatives is a gradual process that poses various conceptual and methodologic challenges along the way. It is clear, for example, that engaging in multilevel analysis has challenged CPHHD investigators, especially in their efforts to apply theoretical concepts to practical settings.

Challenge: providing proper explanatory schemes for observed multilevel effects. Many researchers agree that the most important challenge for multilevel analysis is not merely to apply advanced statistical models but also to provide proper theoretical frameworks for framing studies. This is especially challenging because it is very easy to draw conclusions based on an ecologic fallacy when trying to explain neighborhood effects at a high level when the actual effect-modifiers are low-level factors associated with "neighborhood." Ecologic fallacy arises when inferences about low-level factors, such as SES, are made from high-level factors, such as ZIP code or census tract. Sound theoretical frameworks can provide the scaffolding that guides the development of research questions, collection of data, and the analytic process. One approach is taken by researchers at the University of Pennsylvania, who have used the Systems Model of Clinical Preventive Care[45] to frame a study on determinants and interventions to improve discussions about prostate screening. This study is one example of a translational initiative that seeks to implement a novel computer-assisted, patient-oriented behavioral intervention that is informed by a highly transdisciplinary research enterprise. The systems model is an excellent choice for the project, given that it considers individual-, environmental-, and system-level factors that influence behaviors by patients and practitioners that affect health outcomes. Although not specifically used by the CPHHD, the model developed by Hiatt and Breen[24] shares the translational nature of the systems model by considering the continuum of the disease process, from pre-disease to death, and suggests families of interventions that address this continuum.

Challenge: low statistical power for testing neighborhood effects. In some centers, participants are drawn from a relatively small number of relatively homogeneous census tracts. At Wayne State University, all of the studies are intervention studies, and the studies are powered to detect differences among interventions, not the effects of neighborhoods. There are small differences between the census tracts from which the participants were drawn, and in each study there may be too few tracts to detect neighborhood effects. This challenge is presented here as a cautionary tale: Health disparities researchers need to be aware of the effects of neighborhood characteristics on statistical power, and these characteristics need to be considered in calculating sample size.

Challenge: heterogeneous variable representation. Whenever possible, the CPHHDs would like to avoid excluding variables simply because they were measured or collected at different levels or used different coding schemes. How variables are defined at one level (e.g., the neighborhood level) so that they may be used in analyses with variables at other levels (e.g., the individual level) poses a challenge to those engaged in multilevel analyses. The University of Chicago CPHHD is faced with determining which features of the neighborhood built-environment (i.e., neighborhood level) are most salient to women's individual levels of felt loneliness, depression, and perceived stress. More specifically, they would like to understand the relationships between the neighborhood social environment—measured both at the individual level (with measures of women's perceived neighborhood safety, social cohesion, collective efficacy) and at the neighborhood level (with area major-crime rates related to violence such as homicide and sexual assault)—and psychosocial-stress response, measured at the individual level (determined both subjectively and objectively). The University of Chicago CPHHD's solution to the challenge is to gather data in a number of ways to provide as much flexibility as possible in selecting and constructing variables for analysis.

Challenge: the need for new multilevel-analysis methods. The increasing interest in translational research, which encompasses the continuum of bench to bedside to populations, highlights the importance of extending current multilevel research methods in new directions. The University of Chicago CPHHD, for example, is developing new methods to correlate patterns and features of dynamic cortisol metabolism with cumulative genetic-expression alterations in breast cancer tissue pathology (e.g., intranuclear glucocorticoid receptor activation immunohistology). Those researchers are working with faculty associates on the University of Chicago campus to expand the methods of hierarchical linear models to allow for the inclusion of variables from molecular to community levels on each research subject. This endeavor brings together pathologists, geneticists, social and behavioral scientists, statisticians, and immunologists to develop a new multilevel analytic approach.

Summary

This paper has described several challenges faced by researchers at the CPHHDs as they pursue rigorous programs of health disparities research in a variety of domains. Each of these challenges represents an opportunity for transdisciplinary science to evolve. For example, the substantive data issues that pervade multilevel disparities research could not be addressed without the collaboration of social scientists, data-systems experts, clinicians, and others. But this collaboration is not a simple multidisciplinary one in which each specialist practices his or her craft. Rather, these collaborations require the transcendence of each researcher's domain. Thus, while the challenges presented here may not be unique to multilevel health disparities research, the environment within which they emerged, and in many cases met, is unique. Defining and working through these challenges suggests three strengths of this work and this paper.

First, the CPHHDs collectively offer examples of how these challenges are met within the initiative, but, just as importantly, they offer an extensive compendium of issues that other health disparities researchers should consider, particularly in transdisciplinary environments such as the CPHHD initiative. The work put into rigorous multilevel approaches to health disparities research, exemplified by the efforts reported here, is contributing to a better understanding of health disparities: where they come from, whom they affect and why, and how they might be reduced. Even so, the diversity of the challenges and solutions described here suggests a degree of uniqueness that depends heavily on the research domain under investigation. While the story of multilevel analysis in health disparities research, told through the experience of the CPHHD centers, is compelling, it is not the last chapter. Investigators are urged to be watchful for challenges unique to their research and to consider other solutions that are not described here. It is hoped that this paper stimulates the recognition that such vigilance is a necessary component of health disparities research and of multilevel research approaches in general.

Second, the CPHHDs now have extensive, hands-on experience with multilevel research. There are numerous reports on multilevel research theory and analytic methods, but relatively few that provide insight into the practical, day-to-day problems of conducting this kind of work. This paper provides such a report that, again, is intended to be of value to the broader research community, not just to those currently working in health disparities.

Finally, the CPHHD program facilitates cross-center collaboration in health disparities research, and the centers have in turn taken up the mantle of collaboration. Researchers at the CPHHDs have worked on finding and sharing solutions to the practical and theoretical challenges in multilevel research, not only as it applies to health disparities, but to other research domains as well.

The CPHHD experience suggests the need for new directions in evaluating transdisciplinary science. At the least, a transdisciplinary research evaluation "toolkit" initiated through this endeavor would provide a useful and constructive model for investigators and funding agencies. When fully developed, such a toolkit would contain quantitative tools, such as validated scales that could be used in creating evaluation instruments, as well as qualitative tools, such as semi-structured questionnaires that could be used to elicit attitudes and opinions. The toolkit could be framed within a methodology for evaluating transdisciplinary science so that any evaluations would be as accurate and robust as possible. This methodology would borrow from the best traditions of research evaluation, but would need to extend the boundaries to include new methods and to apply existing methods in new ways.

Transdisciplinarity does not exist automatically, nor all at once; rather, it emerges over time, within and among individuals, groups of individuals, departments, schools, institutions, and organizations. Ultimately, there is a need to foster team science so that transdisciplinarity is given a chance to emerge. The authors' experience with conducting multilevel research in health disparities underscores this need. As an example, their survey-based evaluation efforts have provided insight into the number and types of collaborations across the CPHHD program, but were unable to capture the evolution of team science, even with annual evaluations, which had focused on such characteristics as publication counts and self-reported data on collaboration. This experience suggests that instruments requiring self-report may not be the optimal way to capture team science-related evaluation data, and the authors are hopeful that the social-network analyses will provide more substantive information, particularly with regard to the scientific collaboration and integration that are central to transdisciplinary research.

However, two potentially more-powerful approaches would be the use of temporal social-network analysis and a formal bibliometric analysis of not only published but cited publications as ways to investigate the emergence of "new science." These approaches would be particularly valuable, given that increasing numbers of CPHHD investigators identified multilevel research as a major challenge. A final lesson learned from the authors' experience is that multilevel research should be considered in a transdisciplinary context. Multilevel research has often been conducted without consideration of this context, perhaps to its detriment.[46] The CPHHD initiative (and others like it) offers the opportunity for conducting multilevel research in a variety of application domains, within a new, rigorous, and inherently transdisciplinary environment.

No financial disclosures were reported by the authors of this paper.

References

1. Mensah GA, Mokdad AH, Ford ES, Greenlund KJ, Croft JB. State of disparities in cardiovascular health in the U.S. Circulation 2005;111:1233–41.
2. Sharma S, Malarcher AM, Giles WH, Myers G. Racial, ethnic and socioeconomic disparities in the clustering of cardiovascular disease risk factors. Ethn Dis 2004;14:43–8.
3. Bradley CJ, Given CW, Roberts C. Race, socioeconomic status, and breast cancer treatment and survival. J Natl Cancer Inst 2002;94:490–6.
4. CDC. Racial/ethnic disparities in diagnoses of HIV/AIDS—33 states, 2001–2004. MMWR Morb Mortal Wkly Rep 2006;55:121–5.
5. CDC. Racial/ethnic disparities in infant mortality—U.S., 1995–2002. MMWR Morb Mortal Wkly Rep 2005;54:553–6.
6. Ananthakrishnan AN, Schellhase KG, Sparapani RA, Laud PW, Neuner JM. Disparities in colon cancer screening in the Medicare population. Arch Intern Med 2007;167:258–64.
7. Sassi F, Luft HS, Guadagnoli E. Reducing racial/ethnic disparities in female breast cancer: screening rates and stage at diagnosis. Am J Public Health 2006;96:2165–72.
8. Fernandez E, Schiaffino A, Borrell C, et al. Social class, education, and smoking cessation: long-term follow-up of patients treated at a smoking cessation unit. Nicotine Tob Res 2006;8:29–36.
9. Honjo K, Tsutsumi A, Kawachi I, Kawakami N. What accounts for the relationship between social class and smoking cessation? Results of a path analysis. Soc Sci Med 2006;62:317–28.
10. Kesteloot H. Social class, all-cause, cardiovascular and cancer mortality: the importance of cigarette smoking. Acta Cardiol 2003;58:285–7.
11. Heisler M, Faul JD, Hayward RA, Langa KM, Blaum C, Weir D. Mechanisms for racial and ethnic disparities in glycemic control in middle-aged and older Americans in the health and retirement study. Arch Intern Med 2007;167:1853–60.
12. Giles T, Aranda JM Jr, Suh DC, et al. Ethnic/racial variations in blood pressure awareness, treatment, and control. J Clin Hypertens 2007;9:345–54.
13. Stuart-Shor EM, Nannini A, Ostrem M, Russell GE, Mittleman MA. The prevalence of blood pressure and cholesterol monitoring in Boston among non-Hispanic blacks, Hispanics, and non-Hispanic whites. Ethn Dis 2006;16:375–83.
14. Holt K, Franks P, Meldrum S, Fiscella K. Mammography self-report and mammography claims: racial, ethnic, and socioeconomic discrepancies among elderly women. Med Care 2006;44:513–8.
15. Rauscher GH, Johnson TP, Cho YI, Walk JA. Accuracy of self-reported cancer screening histories: a meta-analysis. Cancer Epidemiol Biomarkers Prev 2008;17:748–57.
16. USDHHS. Healthy People 2010, 2nd ed. www.healthypeople.gov/publications/.
17. Keppel KG, Pearcy JN, Wagener DK. Healthy People 2000: trends in racial and ethnic-specific rates for the health status indicators: U.S., 1990–1998. Statistical Note No. 23. Hyattsville MD: National Center for Health Statistics, 2002.
18. Silva A, Whitman S, Margellos H, Ansell D. Evaluating Chicago's success in reaching the Healthy People 2000 goal of reducing health disparities. Public Health Rep 2001;116:484–94.
19. Barnett E, Halverson J. Disparities in premature coronary heart disease mortality by region and urbanicity among black and white adults ages 35–64, 1985–1995. Public Health Rep 2000;115:52–64.
20. Cooper R, Cutler J, Svigne-Nickens P, et al. Trends and disparities in coronary heart disease, stroke, and other cardiovascular diseases in the U.S.: findings of the National Conference on Cardiovascular Disease Prevention. Circulation 2000;102:3137–47.
21. Liao Y, Cooper RS. Continued adverse trends in coronary heart disease mortality among blacks, 1980–91. Public Health Rep 1995;110:572–9.
22. Newman LA, Mason J, Cote D, et al. African-American ethnicity, socioeconomic status, and breast cancer survival: a meta-analysis of 14 studies involving over 10,000 African-American and 40,000 white American patients with carcinoma of the breast. Cancer 2002;94:2844–54.
23. Bloche MG. Health care disparities—science, politics, and race. New Engl J Med 2004;350:1568–70.
24. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–S150.
25. Subramanian SV, Chen JT, Rehkopf DH, Waterman PD, Krieger N. Racial disparities in context: a multilevel analysis of neighborhood variations in poverty and excess mortality among black populations in Massachusetts. Am J Public Health 2005;95:260–5.
26. Fone DL, Lloyd K, Dunstan FD. Measuring the neighbourhood using UK benefits data: a multilevel analysis of mental health status. BMC Public Health 2007;7:69.
27. Acevedo-Garcia D, Lochner KA, Osypuk TL, Subramanian SV. Future directions in residential segregation and health research: a multilevel approach. Am J Public Health 2003;93:215–21.
28. Anderson NB. Levels of analysis in health science. A framework for integrating sociobehavioral and biomedical research. Ann N Y Acad Sci 1998;840:563–76.
29. Poortinga W, Dunstan FD, Fone DL. Perceptions of the neighbourhood environment and self rated health: A multilevel analysis of the Caerphilly Health and Social Needs Study. BMC Public Health 2007;7:285.
30. Fitzsimon N, Shiely F, Corradino D, Friel S, Kelleher CC. Predictors of self-reported poor mental health at area level in Ireland: a multilevel analysis of deprivation and social capital indicators. Ir Med J 2007;100:49–52.
31. Blumenthal RN, Do DP, Finch B, Martinez A, Edlin BR, Kral AH. Community characteristics associated with HIV risk among injection drug users in the San Francisco Bay area: a multilevel analysis. J Urban Health 2007;84:653–66.
32. Bell JF, Zimmerman FJ, Almgren GR, Mayer JD, Huebner CE. Birth outcomes among urban African-American women: a multilevel analysis of the role of racial residential segregation. Soc Sci Med 2006;63:3030–45.
33. Bird CE, Rieker PP. Gender and health: the effects of constrained choices and social policies. Cambridge: Cambridge University Press, 2008.
34. McClintock MK, Conzen SD, Gehlert S, Masi C, Olopade F. Mammary cancer and social interactions: identifying multiple environments that regulate gene expression throughout the life span. J Gerontol B Psychol Sci Soc Sci 2005;60:32–41.
35. Kleinenberg E. Heat wave: a social autopsy of disaster in Chicago. Chicago: University of Chicago Press, 2002.
36. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
37. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
38. Warnecke RB, Oh A, Breen N, Gehlert S, et al. Approaching health disparities from a population perspective: the NIH Centers for Population Health and Health Disparities. Am J Public Health 2008. In press.
39. Stokols D, Fuqua J, Gress J, et al. Evaluating transdisciplinary science. Nicotine Tob Res 2003;5(1S):S21–S39.
40. Stokols D. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
41. Gehlert S, Rebbeck T, Lurie N, Warnecke R, Paskett E, Goodwin J. Cells to society: overcoming health disparities. Washington DC: National Cancer Institute, 2007.
42. Sampson RJ, Raudenbush SW, Earls F. Neighborhoods and violent crime: a multilevel study of collective efficacy. Science 1997;277:918–24.
43. Truong KD, Sturm R. Alcohol outlets and problem drinking among adults in California. J Stud Alcohol Drugs 2007;68:923–33.
44. Cohen D, McKenzie TL, Sehgal A, Williamson S, Golinelli D, Lurie N. Park use and physical activity in a sample of public parks in the city of Los Angeles. Am J Public Health 2007;97:509–14.
45. Walsh JME, McPhee SJ. A systems model of clinical preventive care: an analysis of factors influencing patient and physician. Health Educ Q 1992;19:157–75.
46. Gehlert S, Murray A, Sohmer D, McClintock M, Conzen S, Olopade O. The importance of transdisciplinary approaches for understanding and ameliorating health disparities. J Health Soc Policy 2008. In press.

The Science of Team Science

Commentary on Measurements of Scientific Readiness

Timothy C. Hays, PhD

Introduction

Some topics in this supplement to the *American Journal of Preventive Medicine*[1–3] focus on the rigorous analysis of various contextual factors influencing the design, implementation, and sustainability of transdisciplinary research; however, an additional area of scientific exploration that may benefit Team Science and the transdisciplinary research field is the formal investigation of factors that elucidate when scientific areas are merging and/or ripe for collaborative study. This precursor of collaboration readiness could play a significant role in understanding why and how team science collaborations breakdown or thrive.[1] If fields of science have not sufficiently evolved toward one another or their underlying support structures are incongruous, it may be difficult or impossible to initiate and maintain cross-disciplinary research even though the participants are eager and other readiness challenges have been successfully met. Understanding the underlying *readiness* markers could go a long way in determining why some collaborative projects fail or succeed, forecasting why and/or when some projects should be initiated, and identifying collaborative opportunities that were otherwise unknown. These findings could be used to help identify research opportunities within and across scientific fields. After gaining insight into when scientific areas are converging, having tools or methodologies for matching compatible investigators for successful Team Science would further aid the process.

The following commentary, from an outside, but interested, observer of the transdisciplinary research field, focuses on a generalized interpretation of two potential serial phases of team science. These phases do not cover the breadth of research being done on the science of team science, but instead highlight arenas of research that might add potentially significant domains of inquiry.

Phase 1

→ Investigators determine that a team-science approach might benefit their research.
→ Funding organizations look for new, emerging, or innovative approaches to research that could increase the potential for more, improved, or quicker research outcomes.

Study elements. Investigate the metrics or identifiers that are used or could be used by researchers and funding organizations to determine when areas of science are ripe for collaborative research and, more specifically, transdisciplinary research.

One of the initial challenges for Phase 1 is to identify good metrics or science markers that can demonstrate connections between fields of research. Some metrics might include markers of when: (1) two scientific fields share system pathways or molecular components, (2) the scientific methodologies overlap in some key way, or (3) the conceptual research questions or ideology are the same (e.g., studying the genetic drivers for reproductive behavior across plant and animal species). The next step would be to determine when the metrics identify fields of research, narrow or broad, that are converging or have overlap. Based on findings derived from analyses hypothesized above, can these metrics be used to determine whether the research areas are ready for collaborative investigation?

Companies, publishers, and organizations have already begun developing technologies (e.g., research profiling[4–6]) that can mine elements of research including published articles to assist in identifying when, for example, similar words or concepts (e.g., proteins or methodologies) begin to appear in historically unrelated fields of research. However, more investigative work needs to be done on whether the overlap of a few concepts, citation connections (bibliometrics[7]), or methodologies is sufficient and predictive of merging areas of science and additionally whether these areas of science would benefit from collaborative research. Nonetheless, the development of these tools will likely have benefit for most scientists in their attempt to understand the ever expanding number of research papers and information being collected and published. Without the emergence of these tools, one can envision researchers moving toward microcosm fields of expertise, narrowing their scientific scope to help establish or maintain clear parameters for what constitutes the body of knowledge they can justifiable defend.

An initial area of inquiry for scientific readiness might include a review of successful and unsuccessful transdisciplinary research (or add questions to any

From the Office of Portfolio Analysis and Strategic Initiatives, NIH, Bethesda, Maryland

Address correspondence and reprint requests to: Timothy C. Hays, PhD, NIH, 1 Center Drive, Building 1, Room 201, Bethesda MD 20892. E-mail: thays@od.nih.gov.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.016

similar review studies that may already be underway). An understanding about the scientific events that led to the collaborative efforts and any scientific-readiness cues that were employed could provide insight that may well be used more systematically to establish successful teams. Using models or novel approaches based on these metrics of scientific readiness, as associated with successful or unsuccessful collaborative research projects, could provide suggestive information about when the opportunity for research collaboration is ripe.

This line of thought leads to additional questions such as: (1) What new analytical tools could assist in our understanding of readiness cues? (2) Are there hindrances to accessing the data needed for proper analyses, developing models, or testing hypotheses? For example, would a uniform interface with access to all journal articles (or summaries) be necessary for practical, comprehensive data mining by investigators and funding organizations to unearth connections? Access to research descriptions, publications, data sets, and methodology repositories, for example, may prove essential for capturing the proper metrics. (3) Can new technologies be transformative in the way we identify collaborative areas of research? (4) Will the output of these tools provide more refined definitions of what constitutes relatedness (e.g., related papers, findings, or researchers) in a way that is now very difficult due to both the sheer abundance of scientific information and the difficultly in connecting the information from disparate locations or repositories?

If these tools are successful in identifying scientific convergence, investigators and funding organizations will next need to know which researchers in the respective fields are the most appropriate for establishing a team to move the science forward.

Phase 2

→ Investigators use various methods to identify a researcher with the right expertise and compatibility to initiate a research partnership.
→ Funding organizations use various methods to identify the "right" researchers who can carry out successful (transdisciplinary or collaborative) research when Phase 1–type opportunities appear to exist.

Study elements. Investigate the metrics or identifiers that an investigator or funding organization uses or could use to determine who the best collaborator(s) would be for their conceptualized research idea. Investigate which metrics or combination thereof could serve as forecasters of successful collaboration. Determine the best methods to bring together disciplines and people when areas of science have been identified as promising for transdisciplinary or team research.

Previous research findings on the contextual issues related to the science of team science are likely to offer insights into what tools could further benefit the process of linking the right investigators. For example, should there be a broad researcher database or connected set of databases that serve as communities of practice (CoP[8])? These CoPs could incorporate not only an investigator's research publications but also their current contact information, their self identified expertise and interests, and possibly recommendations or comments from other researchers. This proposition is not new and available tools are already appearing on the Internet (some specific to research[9]). One functional question that arises is: what are the essential metrics within the lists of skills, interests, publications, or comments that are sufficient to identify an individual as the "right person" for a collaborative project?

Although the theory above constitutes what could be termed as a "top-down" approach to deriving scientific opportunities, the tools discussed above could provide information leading to "bottom-up" opportunities or insights as well. For example, an investigator looking for transdisciplinary opportunities could use these tools to establish new research theories (top-down). At the same time, another researcher with a known scientific dilemma might use the tools to understand whether theories, techniques, findings, or molecules from other domains of science could lead to insights and possible experimentation possibilities (bottom-up).

Clearly there are many challenges not only for the development of these new technologies but also in the data that are available for mining and the processes used to identify metrics. However, there seems to be benefit in establishing clear methodology to understand the evolution of scientific interconnectedness, especially as redundancies in systems (i.e., the same DNA sequences found in humans and rats; the innate behavioral fear response in multiple species elicited by snakes) lead to more overlap in research fields. A more firm understanding of scientific readiness combined with the known contextual factors that facilitate and/or hinder transdisciplinary or team science could ultimately assist in the long term establishment and maintenance of successful cross disciplinary teams.

In summary, if transdisciplinary investigation is to be more fully realized, it will be critical to understand the foundation of scientific readiness. The 2006 establishment of the new Division of Program Coordination, Planning, and Strategic Initiatives (DPCPSI) at the NIH offers a central location for NIH to begin to investigate some of the new ideas highlighted above. If facilitative tools are successfully implemented on a broad scale at institutions and agencies, it could help demonstrate scientific necessity for crossing traditional funding and "departmental" boundaries. The cost of establishing and maintaining transdisciplinary teams may to some seem high, but the potential of such research is already evident (e.g., mechanical engineering techniques being applied to the development of artificial organs and limbs). Developing rigorous methods and models may ultimately help researchers and funding agencies/institutions foster new domains of inquiry and new research findings for the betterment of all mankind.

No financial disclosures were reported by the author of this paper.

References

1. Stokols D, Hall KL, Taylor B, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
2. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
3. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med 2008;35(2S):S243–S249.
4. Giles J. Key biology databases go wiki. Nature 2007;445:691.
5. Collexis High Definition Search. Available at: www.Collexis.com.
6. SyynX Research Profiling. Scientific Competence Profiles for External Presentation. Available at www.syynx.com/produkte3.asp.
7. Bibliometrics. From Wikipedia, the free encyclopedia. Available at: en.wikipedia.org/wiki/Bibliometrics.
8. Community of practice. From Wikipedia, the free encyclopedia. Available at: en.wikipedia.org/wiki/Community_of_practice.
9. Biomed Experts. Available at: www.biomedexperts.com/.

Systems Thinking to Improve the Public's Health

Scott J. Leischow, PhD, Allan Best, PhD, William M. Trochim, PhD, Pamela I. Clark, PhD, MSPH, Richard S. Gallagher, BS, Stephen E. Marcus, PhD, Eva Matthews, MPH

Abstract: Improving population health requires understanding and changing societal structures and functions, but countervailing forces sometimes undermine those changes, thus reflecting the adaptive complexity inherent in public health systems. The purpose of this paper is to propose systems thinking as a conceptual rubric for the practice of team science in public health, and transdisciplinary, translational research as a catalyst for promoting the functional efficiency of science. The paper lays a foundation for the conceptual understanding of systems thinking and transdisciplinary research, and will provide illustrative examples within and beyond public health. A set of recommendations for a systems-centric approach to translational science will be presented.
(Am J Prev Med 2008;35(2S):S196–S203) © 2008 American Journal of Preventive Medicine

Introduction

"Public health asks of systems science, as it did of sociology 40 years ago, that it help us unravel the complexity of causal forces in our varied populations, and the ecologically layered community and societal circumstances of public health practice."[1]

Green's quote suggests that to improve public health, it will be necessary to gain a greater understanding of the complex adaptive systems involved in both causing and solving public health problems.[2] For example, preventing and containing pandemic influenza requires collaboration across a wide array of disciplines and fields, including global surveillance to catch new outbreaks, rapid laboratory analysis of new viral strains so that effective medications can be developed, and the creation of expansive communications and informatics infrastructures so that communities can prepare and react effectively. Each separate activity to address pandemic influenza is necessary but insufficient in itself. However, when viewed together, the structures and functions to prevent and contain pandemic influenza represent an ever-changing complex adaptive system whose sum is greater than the parts. Indeed, millions—and perhaps billions—of lives depend on how well that complex system works.

The increasing emphasis on systems thinking as an organizing rubric reflects a confluence of trends among very different fields that have begun to emphasize systems thinking, including business, engineering, physics, military science, agriculture, weather forecasting and public health.[3,4] While there is no single discipline for systems thinking, there are some fundamental systems-thinking perspectives and approaches that are shared across fields: (1) increased attention to how new knowledge is gained, managed, exchanged, interpreted, integrated, and disseminated; (2) emphasis on a network-centric approach that encourages relationship-building among and between individuals and organizations across traditional disciplines and fields in order to achieve relevant goals and objectives; (3) the development of models and projections, using a variety of analytic approaches (e.g., differential equations, agent-based modeling, system-dynamics modeling) in order to improve strategic decision making; and (4) systems organizing in order to foster improvements in organizational structures and functions.[2–4]

Consistent with this systems perspective, and echoing Rosenfield's[5] benchmark definitions of multidisciplinarity, interdisciplinarity, and transdisciplinarity, Stokols[6] in this supplement to the *American Journal of Preventive Medicine* describes transdisciplinary research as a "process in which team members representing different fields work together over extended periods to develop shared conceptual and methodologic frameworks that not only integrate but also transcend their respective disciplinary perspectives." Given the profoundly different ways that scientists collect data and define new knowledge within disciplines, along with the many different discipline-based assumptions about the nature of that knowledge, transdisciplinarity reflects an episte-

From the Arizona Cancer Center (Leischow) and the Department of Family and Community Medicine (Matthews), University of Arizona, Tucson, Arizona; the Centre for Clinical Epidemiology and Evaluation, Vancouver Coastal Health Research Institute (Best), Vancouver British Columbia, Canada; the Department of Policy Analysis and Management, Cornell University (Trochim), and Gallagher and Associates (Gallagher), Ithaca, New York; the University of Maryland (Clark), College Park; and the Tobacco Control Research Branch, Behavioral Research Program, Division of Cancer Control and Population Sciences, National Cancer Institute (Marcus), Rockville, Maryland

Address correspondence and reprint requests to: Scott J. Leischow, PhD, Professor, Arizona Cancer Center, The University of Arizona, 1515 N. Campbell Avenue, Room 4943, Tucson AZ 85724. E-mail: sleischow@azcc.arizona.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.014

mology, or theory of knowledge, that has profound implications for how new knowledge is collected, synthesized, interpreted, and disseminated. This is not to suggest that unidisciplinary, reductionist science is no longer relevant. Rather, the increased emphasis on science that is transdisciplinary, translational, and network-centric reflects a recognition that much, if not most, disease causation is multifactorial, dynamic, and nonlinear.[7] Indeed, scientific silos, or compartmentalized knowledge, have the potential to impede understanding of the complex inter-relationships among variables.[8]

It is perhaps neither possible nor desirable to eliminate the silos of science, but there is increasing recognition that it is essential to link them and to recognize that they represent components of a larger system.[2] That is, transdisciplinary science represents a necessary but insufficient aspect of complex adaptive public health systems. Achieving effective and lasting advances in public health clearly depends on the knowledge gained through transdisciplinary science (e.g., the biological and behavioral causes of tobacco dependence, or social and biological factors that cause the spread of communicable diseases). But achieving those gains also requires making strategic decisions about which complex scientific questions will lead to the greatest public health gains, how new discoveries can be disseminated effectively, and what structures and functions are needed to deliver the new knowledge. The opinion that complex challenges cannot be solved by reductionist approaches alone reflects an orientation toward systems thinking that Senge[9] called a "fifth discipline." And this fifth discipline is highly consistent with the principles of systems thinking and cybernetics that were discussed long ago by von Bertalanffy,[10,11] Wiener,[12] and Ackoff,[13] and more recently by Leischow and Milstein,[2] Sterman,[14] Midgely,[15] and Green.[1]

Systems Thinking for Hurricanes and H5N1 Avian Influenza

Because systems thinking is often difficult to conceptualize, exemplars of both systems design and systems analysis can serve as valuable models for those who are unfamiliar or even perplexed by what is meant by the term. While many examples exist, weather forecasting and the prevention of communicable disease will be described here.

Weather Forecasting

Perhaps one of the most advanced transdisciplinary collaboratives that is fundamentally oriented toward the conceptual framework of systems thinking is weather modeling and forecasting.[16] Networks of organizations and scientists from around the world work together to understand the complexity of weather patterns so that more accurate and timely weather forecasts can be made. The Weather Research & Forecasting Model group employs a type of translational model whereby new discoveries made within a particular discipline (e.g., oceanography) are linked together, so that complex relationships can be determined by transdisciplinary teams of scientists (i.e., physicists, atmospheric chemists, geographers). Models can be developed that explain the data, and optimized models can then be disseminated to specific end-users and the public. Understanding the interplay of solar activity, land masses, water temperatures, wind flow, and other natural forces has made it possible—via complex and intensive computational modeling—to develop predictive weather models that have both saved lives and reduced economic devastation. Indeed, the National Oceanic and Atmospheric Administration, in collaboration with more than 150 universities, implemented a new computer system that can model ever-more-complex data (e.g., wind activity at specific elevations, humidity differences between night and day, the amount of Arctic ice) in order to develop improved forecasts.[17]

An integral part of the weather forecasting system is communication with the public. The example of Hurricane Katrina serves as a reminder that having accurate forecasting and analysis of a complex weather system does not necessarily translate into an effective use of that information. Indeed, Katrina was a tragic example of the dire consequences of a failed delivery component of the system. Many years of investment into collecting data from a variety of sources led to accurate forecasts, which in turn gave millions of people in Katrina's path time to escape; however, the application of that knowledge by federal, state, and local officials failed. The devastating outcome was a reminder that a complex system worth investigating lends itself to large-scale organizational change as a result of new knowledge. This phenomenon is both the promise and the challenge of systems thinking.

Preventing the Next Global Pandemic

In 1918–1919, the Spanish influenza pandemic spread globally in waves, killing between 50 and 100 million people worldwide.[18,19] This viral infection was the last pandemic in the U.S., and if history is consistent, there will be additional pandemics in the future. In recent years, the H5N1 Avian influenza has been of paramount concern because it is deadly to humans and could rapidly spread if mutations allow it to easily pass from human to human. Fortunately, as in the weather forecasting example above, public health agencies worldwide have recognized this risk and have implemented systems—including transdisciplinary teams of scientists—to prevent or minimize the risk of a future communicable-disease pandemic.

In the U.S., the CDC coordinates a comprehensive surveillance-and-response system to anticipate and manage influenza outbreaks. One component of this system is BioSense,[20] a real-time surveillance system that links data from local and national sources to identify and track new and existing influenza outbreaks. Another component, also under the supervision of the CDC, is the Laboratory Response Network,[21] an integrated system of laboratories at the local, national, and international level, that serves as a rapid reporting-and-response infrastructure for communicable disease and bioterrorism. This comprehensive system assures that "hot spots" of influenza will be identified early, so that local healthcare systems can mobilize, and policymakers can take appropriate action to prevent the spread of disease. In addition, the NIH has increased its investment in the development of new drugs to treat influenza, and has created an initiative called Models of Infectious Disease Agent Study, a "collaboration of research and informatics groups to develop computational models of the interactions between infectious agents and their hosts, disease spread, prediction systems, and response strategies."[22]

The overall goal of these and other efforts is to bring together those who are critical to the discovery, development, and delivery of the knowledge, products, and services that will most effectively prevent and treat communicable disease. This comprehensive and multidisciplinary systems approach to preventing a massive outbreak of disease that could kill millions of people depends, like the weather-forecasting system, on (1) massive and rapid data collection from many different sources; (2) rapid communication to a broad array of sources; (3) transdisciplinary science, in order to understand and analyze data from many sources; and (4) modeling of the complex relationships among the components in the system. These four elements are necessary for the creation of more accurate predictions and recommendations that can be used by policymakers to protect the health of the public.

Systems Thinking in Public Health and Learning from ISIS

Despite the promise that systems approaches hold for improved understanding of the complex factors that contribute to health and disease, few systems initiatives have been developed at one of the premier U.S. center for health research—the NIH—to address chronic disease or its causal factors. A recent exception is the pilot Initiative on the Study and Implementation of Systems (ISIS). Aware of the systems-thinking approaches that have been applied in other areas and given the complex nature of tobacco use and tobacco-related disease, the National Cancer Institute (NCI) funded ISIS to explore how systems-thinking approaches might improve the understanding of the factors contributing to tobacco use; to inform strategic decision making about which efforts might be most effective for reducing tobacco use and tobacco-related disease; and to serve as an exemplar for addressing other public health problems. More specifically, ISIS was intended to become a long-term, multi-agency collaboration to create and implement transdisciplinary-systems principles and methods for the discovery, development, and delivery of program and policy interventions within a research-to-practice paradigm.

Developing and Defining the Four Key Areas in Systems Thinking

Given the multiple systems approaches that have been employed to address complex problems (e.g. weather forecasting, communicable disease, managing the economy, conducting military operations), one of the goals of ISIS was to identify what they have in common, so that this information could be used to identify effective ways to improve tobacco control. More specifically, a strategic-planning and development process was put into place to consider existing literature; the efforts of experts in other fields (e.g., the military, business, system dynamics, etc.); and experts across several disciplines within the tobacco-control field.

In addition to focus groups and other formative efforts completed during the first year of ISIS, a process led by noted system-dynamics expert George Richardson[23] was implemented to explore what is meant by a *tobacco control system*. As a result of that process, two important conclusions emerged: (1) understanding and implementing complex systems is all about the relationships among people, collections of information, and even concepts; and (2) these relationships work or do not work as a function of information and how it is communicated. Thus, as the ISIS team began exploring complex relationships via system-dynamics thinking and modeling, two of what became four key principles emerged very rapidly: Without effective information and knowledge exchange, social networks do not function effectively; in addition, when social networks oriented to public health are not functioning effectively as a result of inadequate or dysfunctional information and knowledge exchange, systems that could be effective are compromised and even prevented from achieving their potential positive impact. A perfect example of what can go wrong is the outcome of Hurricane Katrina.

Conversely, when knowledge flow is effective, network performance is better, and systems-level change is possible. An example is community-driven policy change, wherein over the last few decades there has been an increased shared awareness[24] that higher cigarette taxes and restrictions on smoking in public places would result in significant drops in smoking prevalence.

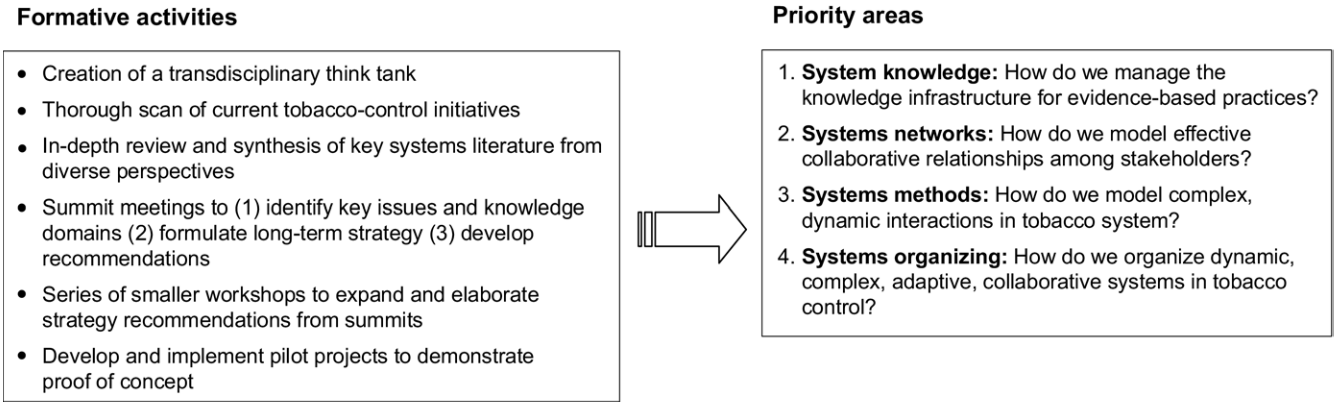


Figure 1. Initiative on the Study and Implementation of Systems (ISIS) strategic-planning activities and key priorities

Consequently, many states and nations focused their tobacco-control efforts on increasing tobacco taxes and legislating bans on smoking in public places.

As a result of the activities in the strategic-planning process, the ISIS group identified four priority areas (Figure 1) that together serve as a synergistic foundation for understanding and improving the public's health from a systems perspective. They do not represent the only possible foundations, and certainly do not represent all of the critical areas within the public health system that require attention, but they do reflect both conceptual and functional areas that together result in a sum greater than their individual contributions.

A brief summary of each area, drawn from the NCI monograph[25] on systems thinking that these authors developed, summarizes the relevance of each to the systems approach that the ISIS team delineated.

1. Managing systems knowledge. The management and transfer of shared knowledge form the basis of interaction between stakeholders in a systems environment. The development of an effective system requires a comprehensive, sophisticated infrastructure for knowledge management and transfer that is based on integrating existing silos of information, and manages both explicit knowledge (what we know we know) and tacit knowledge (what we do not know we know; unconscious lessons from experience). This knowledge environment must be collaborative, in keeping with the needs of the stakeholders it supports, and able to meet the changing needs and methods underlying a systems approach to tobacco control. It must also be evolutionary.

To demonstrate the potentials of a web-based, collaborative-knowledge environment for tobacco control, the NIH and other partners created a cyber-infrastructure to improve the sharing, analysis, and dissemination of tobacco data. This tobacco web portal, currently called the Tobacco Informatics Grid (TobIG), will use state-of-the-science information technology and networking software to link tobacco data, researchers, and resources (e.g., citation indexes, data mining, and visualization software). TobIG is envisioned as a cyber-infrastructure to support a voluntary network, or grid, of tobacco-control stakeholders to data and software/analysis tools. TobIG was conceived to be part of a multicomponent strategy to speed the development and delivery of innovative approaches to tobacco control that would link directly with the larger NCI-funded cancer–bioinformatics grid (caBIG).

2. The power of transdisciplinary and multidisciplinary systems networks. Networks form the backbone of a system by harnessing the power of linking diverse stakeholder individuals and groups. Understanding the formation and management of networks and using that knowledge to foster healthy networks in tobacco control are critical components of a systems environment in public health. To better the understanding of how multidisciplinary and organizational communication and collaboration were occurring in tobacco control, several network projects were implemented by the ISIS team. These projects included Mapping the Tobacco Harm Reduction Network (presented in detail in this supplement[26]); the Global Tobacco Research Network (GTRN); and the Social Network Mapping of Tobacco Control at USDHHS.

Global Tobacco Research Network. The GTRN is a virtual web of interconnected scientists and organizations collaborating in the conduct, synthesis, and dissemination of tobacco-control research in support of a progressive, policy-relevant research agenda. Functioning through its web interface,[27] the program provides network consolidation, information management, and information sharing. One product is the Research Assistance Matching Program (Program RAM), in which mentors are matched with novice researchers.

Social network mapping of tobacco control efforts within USDHHS. A social network analysis was used to delineate the connections among the agencies doing tobacco control work within the USDHHS to identify

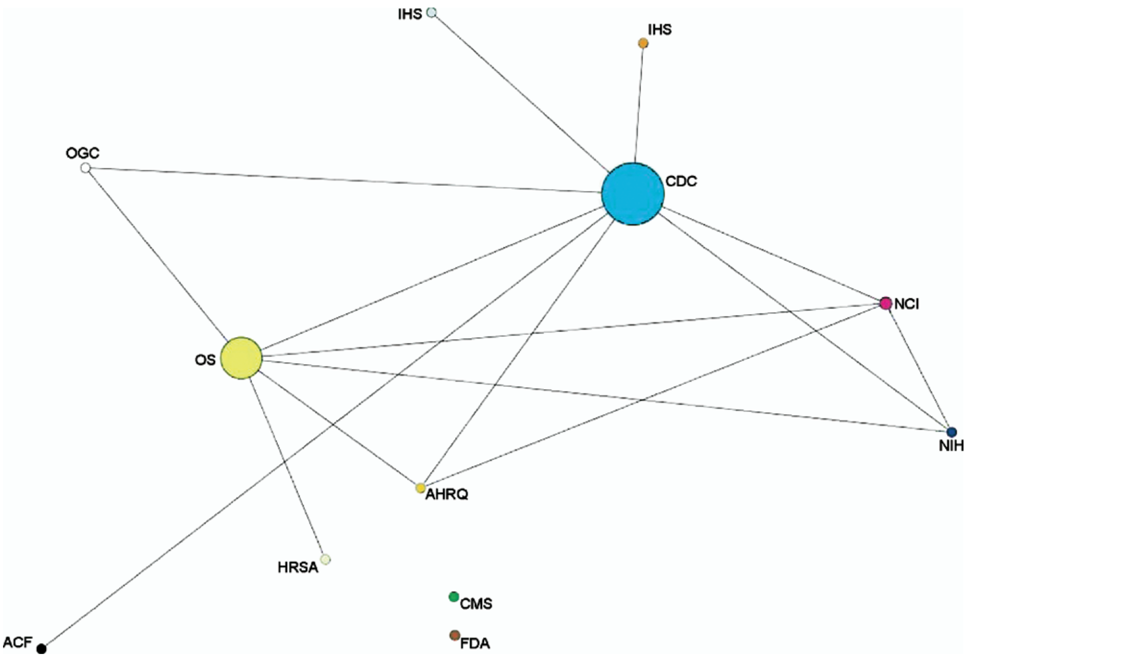


Figure 2. Social-network analysis of tobacco control in the USDHHS

communication gaps and any silos of information (DA Luke, NB Mueller, Saint Louis University, unpublished technical report, 2005). Figure 2 shows the extent of contact between organizations regarding tobacco control on at least a quarterly basis. The size of each node represents *betweenness*, or how often the individuals within an organization act as a bridge between other organizations in the network. The isolates in the display (i.e., the Food and Drug Administration and the Center for Medicare and Medicaid Services) suggest that much can be done to strengthen the tobacco-control communications network with the USDHHS.

3. Methods for analyzing complex systems. System dynamics involve methods that facilitate a more-constructive examination of complex adaptive systems by modeling the behavior of actions and their consequences, both intended and unintended. These methods are particularly well-suited to tobacco control, which encompasses an ongoing struggle with countervailing factors that change over time and can be strengthened. There is considerable promise in a range of systems approaches, including formal system-dynamics modeling techniques and group processes that harness the problem-solving capabilities of multiple stakeholders. These approaches constitute tools that help address problems that are increasingly dynamic and complex.[2,14,15]

To explore this methodology within the ISIS initiative, system-dynamics modeling methods were used to simulate tobacco prevalence and consumption over a 40-year period across various age groups. The ISIS system-dynamics model used a participatory team process among stakeholders to define causal factors in tobacco prevalence, as well as to provide estimates of empirical model data. Formal empirical data from sources such as *Morbidity and Mortality Weekly Report* were used for both model parameters and results validation. A causal-loop model of factors in tobacco prevalence and a formal simulation model of specific shards of this model were developed, using the VENSIM simulation language. One such model is an aging chain of smokers (Figure 3), which explores tobacco use across the lifespan and begins to take into account changes in smoking status, death, and outside influences, in order to inform the modeling process for predicting future tobacco-related morbidity and mortality. This figure, although a bit daunting at first glance, shows the dynamic nature of youth uptake of tobacco through the development of addiction and the potential outcomes through adulthood. Such models can be fit with data (e.g., time to addiction, relapse percentages) to better convey the complexity of the tobacco problem and to identify points in the system where interventions are likely to yield the greatest impact.

4. Systems organizing. Systems organizing reflects an evolution from traditional management theory to a *learning organization*,[3,4] or an adaptive-systems perspective within a systems environment. Its major message is the evolution of current concepts of managing and organizing by transforming traditional top-down, command-and-control structures to encompass network-centric participatory approaches, the effective evaluation of system complexity and dynamics, and explicit attention to knowledge flow and management. Methods of organization are envisioned as a continuum from formal organization in the traditional management sense to self-organizing partnerships or

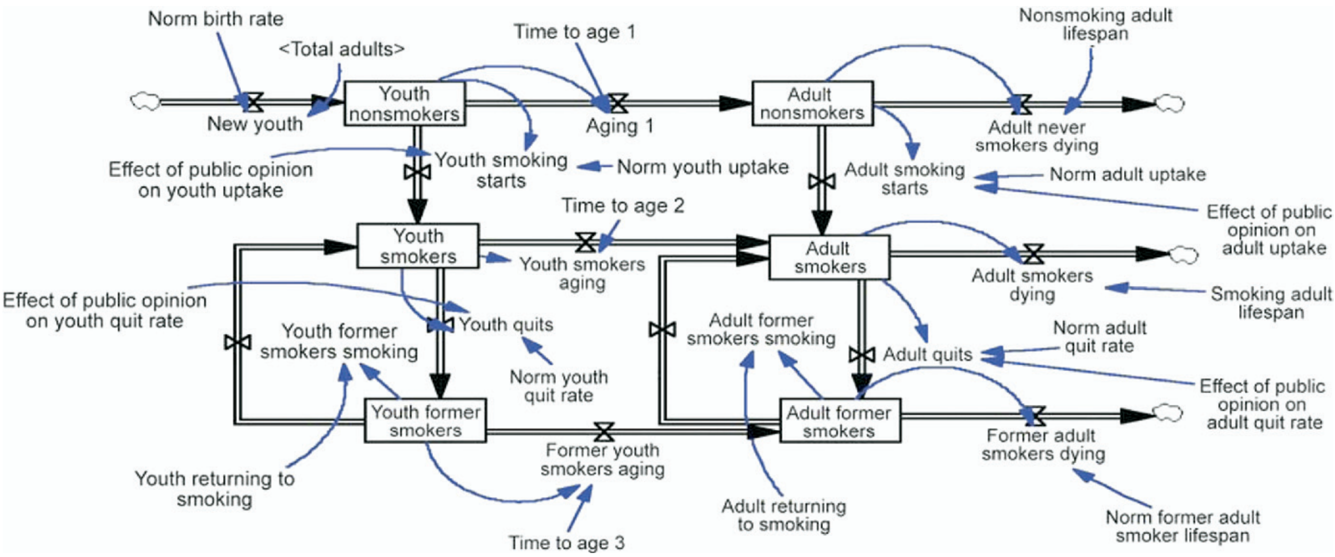


Figure 3. Aging chain of smokers

collaborations. For example, in order to identify the specific genes associated with a particular disease, scientists from multiple disciplines might come together for the purpose of that project and then spin off into other groups to explore other problems. This dynamic process of systems organizing fosters not only increased collaboration to address a particular problem but also an inherent recognition that complex problems require transdisciplinary teams that will change as the problems change.

To explore how systems-organizing approaches could be used in public health contexts, the ISIS project looked at two examples (one appears in Figure 4) that utilized a collaborative, participatory, structured conceptualization methodology known as concept mapping[28,29] to model and graphically depict aggregated clusters of ideas or concepts held by groups (or networks) of stakeholders. This concept-mapping methodology is a good example of a systems-organizing approach that can be utilized either in a face-to-face, real-time group process or in a distributed asynchronous process over the Internet. Concept mapping enables a diverse group of stakeholders to brainstorm a broad spectrum of specific issues that address a mapping focus, organizes these issues through individual sorting and rating, and then synthesizes this input across individuals, using several multivariate statistical methods (multidimensional scaling and hierarchical cluster analysis). The results are graphically presented as conceptual maps. Figure 4 provides an example in which stakeholders associated with state and local tobacco-control efforts developed a conceptual model of the components of a strong tobacco-control program.

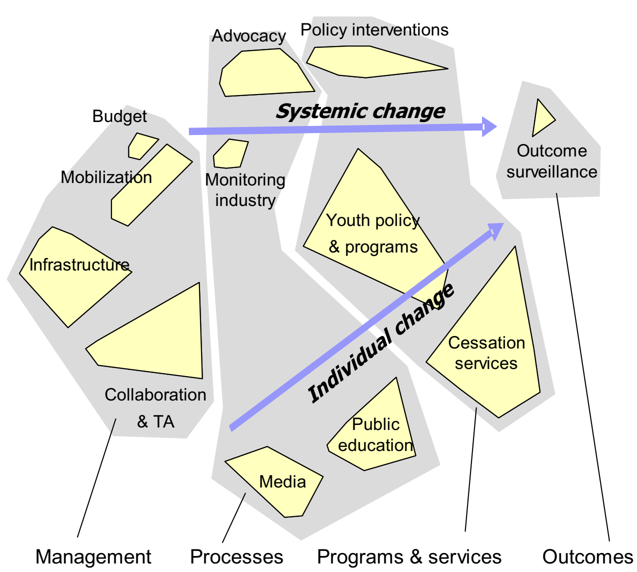


Figure 4. Concept-mapping example

Taking a Systems-Centric Perspective in Science

There is a critical need for government agencies to take a leadership role in fostering increased transdisciplinary and translational collaboration and to employ an approach that recognizes that public health is the culmination of a complex, adaptive federation of systems[22] that no one organization can or should control. While comprehensive, centralized, hierarchical control is not the desired system goal here, there is an essential facilitative role that needs to be played by hierarchical, centralized organizational entities like the federal government, which can provide the leadership essential to developing a framework for action, and encourage and support the process of fostering collaboration among a diverse group of stakeholders. For example, in part as a result of the ISIS effort, the NIH Office of Behavioral and Social Sciences Research has identified systems thinking as fundamental to its strategic planning.[30]

Table 1. ISIS recommendations

ISIS recommendation	Action items
Develop and apply systems methods and processes	Encourage systems thinking theory and research development
	Foster mixed-methods systems thinking
	Conduct participatory systems needs assessments
	Encourage an ecologic perspective on implementation
Build and maintain network relationships	Create multijurisdictional/multilevel networks of networks for systems thinking and action
	Study the networks of networks to determine their effects
	Encourage transdisciplinarity
	Foster systems evaluation
Build system and knowledge capacity	Build capacity for systems thinking
	Expand public health data to enable systems analyses
	Integrate information silos through cyber-infrastructure development
Encourage transformation to a systems culture	Encourage ongoing vision and paradigm evolution
	Rethink prioritizing and funding
	Foster a systems-thinking learning environment
	Address barriers to the adoption of systems thinking
	Engender systems leadership

Similarly, the President's Cancer Panel presented a translational model that reflects a systems approach (discovery, development and delivery), the success of which depends on collaboration both among and between scientists and, just as importantly, among scientists, clinical providers, community providers, policymakers, and the public to ensure that new discoveries can be implemented to improve health in the fastest way possible.[31]

At the completion of the ISIS initiative, the ISIS team developed several recommendations (Table 1) for fostering movement toward a more systems-centric approach to translational science.[25] Some of the recommendations were very concrete, such as studying the networks of networks and developing cyber-infrastructures, and others were conceptual, such as encouraging transdisciplinarity and encouraging ecologic perspectives on implementation.

However, inherent in the ISIS initiative and the resulting recommendations was a recognition that each of the four domains are intertwined and, in fact, depend on each other. This recognition exemplifies systems thinking, because it is oriented to the identification and understanding of complex relationships, not just the dissection of them. Thus, the ISIS team further concluded, a fundamental goal must be the creation of an integrated systems-thinking environment that requires a strong orientation toward new approaches to team science (Figure 5).

The interplay of systems components to improve public health presented in Figure 5 illustrates the need for new approaches to team science that have a transdisciplinary orientation, as well as new approaches to training that integrate reductionist and systems epistemology, that promote a translational orientation, and that are oriented toward the understanding of complex relationships and the fostering of teams to better address public health challenges as complex adaptive systems. Tackling complex public health problems requires transdisciplinary and multidisciplinary teams to understand and address that complexity, and systems thinking is a path for getting them there.

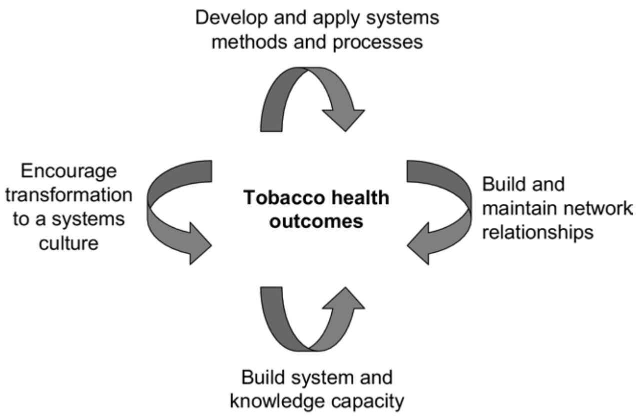


Figure 5. Integrative systems-thinking framework for complex systems in public health

The authors wish to thank the many individuals whose insights led to the ISIS recommendations. In addition, they wish to thank Gregg Moor for his editorial help.

Funding sources were Tobacco Control Research Branch, NCI, and Arizona Cancer Center Support Grant CA023074.

No other financial disclosures were reported by the authors of this paper.

References

1. Green LW. Public health asks of systems science: to advance our evidence-based practice, can you help us get more practice-based evidence? Am J Public Health 2006;96:406–9.
2. Leischow SJ, Milstein B. Systems thinking and modeling for public health practice. Am J Public Health 2006;96:403–5.
3. Best A, Moor G, Holmes B, et al. Health promotion dissemination and systems thinking: towards an integrative model. Am J Health Behav 2003;27(3S):S206–16.

4. Best A, Tenkasi R, Trochim W, et al. Systematic transformational change in tobacco control: an overview of the Initiative for the Study and Implementation of Systems (ISIS). In: Casebeer AL, Harrison A, Mark AL, eds. Innovations in health care: a reality check. New York: Palgrave Macmillan, 2006.
5. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
6. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
7. Barabasi AL. Network medicine—from obesity to the "diseasome." N Engl J Med 2007;357:404–7.
8. Satterfield D, DeBruyn LM. The malignment of metaphor: silos revisited–repositiories and sanctuaries for these times. Am J Prev Med 2005;29:240–1.
9. Senge PM. The fifth discipline: the art and practice of the learning organization. New York: Doubleday, 1994.
10. von Bertalanffy L. The theory of open systems in physics and biology. Science 1950;11:23–9.
11. von Bertalanffy L. A systems view of man: collected essays. Violette PA, ed. Boulder CO: Westview Press, 1981.
12. Wiener N. Cybernetics or control and communication in the animal and the machine. Cambridge MA: MIT Press, 1948.
13. Ackoff RL. Systems, organizations and interdisciplinary research. In: Eckman DP, ed. Systems research and design. New York: Wiley, 1961.
14. Sterman JD. Learning from evidence in a complex world. Am J Public Health 2006;96:505–14.
15. Midgley G. Systemic intervention for public health. Am J Public Health 2006;96:466–72.
16. The Weather Research & Forecasting Model. www.wrf-model.org/index.php.
17. National Weather Service. NCEP's environmental modeling center unveils new national forecast model. www.weather.gov/com/nwsfocus/fs20060711.htm#first.
18. Osterholm MT. Preparing for the next pandemic. N Eng J Med 2005;352:1839–42.
19. The great pandemic: the U.S. in 1918–1919. 1918.pandemicinfluenza.gov/the_pandemic/index.htm.
20. CDC. BioSense. www.cdc.gov/biosense/.
21. CDC. Emergency preparedness & response: the laboratory response network: partners in preparedness. www.bt.cdc.gov/lrn/.
22. National Institute of General Medical Sciences. Models of infectious disease agent study. www.nigms.nih.gov/initiatives/midas/.
23. Richardson GP, Pugh AL. Introduction to system dynamics modeling with DYNAMO. Cambridge: MIT Press, 1981.
24. Krygiel AJ. Behind the wizard's curtain: an integration environment for a system of systems. Washington DC: Institute for National Strategic Studies, 1999. www.dodccrp.org/files/Krygiel_Wizards.pdf.
25. National Cancer Institute. Greater than the sum: systems thinking in tobacco control. Tobacco Control Monograph No. 18. Bethesda MD: USDHHS, NIH, National Cancer Institute. NIH Pub. No. 06-6085, 2007. http://dccps.nci.nih.gov/TCRB/monographs/18/index.html.
26. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
27. Global Tobacco Research Network. www.tobaccoresearch.net.
28. Trochim WM. An introduction to concept mapping for planning and evaluation. Eval Prog Plann 1989;12:1–16.
29. Kane M, Trochim WM. Concept mapping for planning and evaluation. Thousand Oaks CA: Sage Publications, 2007.
30. Office of Behavioral and Social Science Research, NIH. March 1, 2007. obssr.od.nih.gov/content.
31. Reuben SH. Translating research into cancer care: delivering on the promise. 2004–2005 annual report of the President's Cancer Panel. Washington DC: USDHHS, 2005. deainfo.nci.nih.gov/advisory/pcp/pcp04-05rpt/reporttrans.pdf.

The Role of Transdisciplinary Collaboration in Translating and Disseminating Health Research

Lessons Learned and Exemplars of Success

Karen M. Emmons, PhD, Kasisomayajula Viswanath, PhD, Graham A. Colditz, MD, DrPH

Abstract: In the past few decades, significant advances have been made related to understanding, preventing, and treating chronic disease. Given these many advances across multiple disciplines, it is unclear why the potential for yielding substantial reduction in disease has not been achieved overall and across various subgroups. Socioeconomic and racial/ethnic disparities in a wide range of disease outcomes persist, and a number of studies highlight the importance of further improving behavioral risk-factor prevalence on a population level. The goal of this paper is to explore the role of transdisciplinary collaboration in the translation of research related to these vexing public health problems, and, in particular, to explore factors that appear to facilitate effective and sustainable translation. Transdisciplinary collaboration also has great potential to speed the rate of adoption of evidence-based practices. Examples of transdisciplinary collaborations in academic and community settings are provided, along with factors that may influence the long-term outcomes of transdisciplinary efforts.
(Am J Prev Med 2008;35(2S):S204–S210) © 2008 American Journal of Preventive Medicine

Introduction

The past three decades have witnessed substantial progress in reducing the prevalence of preventable disease among adults in the U.S., with contributions from many disciplines.[1] Epidemiologic methods have advanced the understanding of the types, nature, and timing of exposures that increase disease risk.[2] Social and behavioral sciences have provided a perspective on disease causation that goes beyond biomedical approaches, drawing on social–epidemiologic approaches to understand the population distribution of diseases and conditions and using population-based approaches that extend intervention research beyond high-risk populations. Both basic and biomedical science have made significant advances in targeted treatment strategies. Still, the question remains: Isn't there potential for yielding even greater reductions in disease than have been achieved to date? For example, many diseases continue to have disproportionately high prevalence among racial and ethnic minority and lower-socioeconomic groups. In addition, the need to reduce behavioral risk-factor prevalence on a population basis has been recognized.[1,3] It has been estimated that community-based cholesterol interventions are cost effective if blood cholesterol levels are reduced by as little as 2%.[4] The full implementation of currently available cancer prevention and early-detection strategies at the population level could reduce U.S. cancer mortality by approximately 60%.[5,6]

Processes and mechanisms at one level (e.g., at the molecular level) may influence outcomes at another level (e.g., among population subgroups), thus calling for a more-synergistic approach to understanding and solving diseases and conditions. A transdisciplinary approach to research, as proposed by Rosenfield,[7] may be necessary if health promotion and chronic disease prevention efforts are to live up to their potential. A key goal of this paper is to explore the role of transdisciplinary collaboration in the translation of research related to public health, and, in particular, to explore factors that appear to facilitate effective and sustainable translation. Although some examples provided may influence bench-to-bedside translation, the primary focus in this paper is on addressing socioeconomic and racial/ethnic disparities and on closing the evidence-to-practice gap.

Public Health and Transdisciplinary Science

Public health is the ideal environment in which to develop transdisciplinary science. The social–ecologic model,[8] a framework that is widely used for exploring

From the Department of Medical Oncology, Dana-Farber Cancer Institute, and the Department of Society, Human Development, and Health, Harvard School of Public Health (Emmons, Viswanath), Boston, Massachusetts; and the Alvin J Siteman Cancer Center, Washington University School of Medicine (Colditz), St. Louis, Missouri

Address correspondence and reprint requests to: Karen M. Emmons, PhD, Dana-Farber Cancer Institute, 44 Binney Street, LW703, Boston MA 02115. E-mail: karen_m_emmons@dfci.harvard.edu.

0749-3797/08/$–see front matter
doi:10.1016/j.amepre.2008.05.009

the factors that influence health and health behavior, recognizes that health is affected by factors across levels of influence, including intrapersonal, interpersonal, organizational, community, and societal. Although there is work in many areas at each level, a transdisciplinary approach is much more likely to stimulate a search for opportunities for synergy across levels. There has long been a call for linking research and intervention approaches across levels,[1,9] but to date there has been relatively little work in this area. One concern is that tremendous inefficiency is introduced by not considering inter-connections across disciplinary boundaries. For example, if the primary focus of work in obesity and energy balance is on sociocultural factors, eventually the limits of not considering both environmental and physiologic factors will be realized. In addition, the authors agree with Abrams[10] that transdisciplinary approaches to addressing health disparities are crucial, precisely because the causes of disparities are multifactorial. As noted by Kaplan,[11] reducing and eliminating disparities calls for multidisciplinary models that account for how distal factors, such as social and economic policies, and proximal factors, such as genetic make-up and pathophysiology, simultaneously interact to affect population subgroups differently. Transdisciplinary science can contribute to understanding the mechanisms that potentially link these different determinants studied in and from different disciplinary realms and can develop action that may be necessary to ameliorate disease conditions. If a transdisciplinary approach to research in health disparities is not taken, the affected communities are likely to experience enduring disparities, frustration with the process of research, and perceived limited gain/benefit to research participation.

The Development of Transdisciplinary Initiatives

Ruddy and Rhee[12] have identified a number of features that facilitate the development of effective transdisciplinary teams. These include *institutional support* of both transdisciplinary approaches in general and in particular the specific endeavor in which transdisciplinary science is being applied; *team selection*, which includes representation by all relevant disciplines and community group members; *training*, which provide ongoing, cross-disciplinary education and opportunities for problem-based and experiential learning; *common goals*, which serve to functionally operationalize transdisciplinary science through the selection of measurable outcomes and evaluation approaches; and *multidirectional communication*, which recognizes the contributions of all team members on an ongoing basis. Several structural factors also facilitate the development of effective transdisciplinary teams, including having shared space, a reduction of institutional barriers, a strong history of collaboration, and educational and training opportunities for students and staff who can help to break down disciplinary barriers. Examples of how transdisciplinary collaborations have developed in both university and community settings illustrate these principles.

Transdisciplinary Initiatives in University Settings

The Dana-Farber/Harvard Cancer Center

The experience of establishing the Dana-Farber/Harvard Cancer Center (DF/HCC) provides an example of the importance of institutional support for and commitment to transdisciplinary engagement. For more than 30 years, the Dana-Farber Cancer Institute was a single-institution comprehensive cancer center. The National Cancer Institute (NCI) strongly encouraged the formation of a larger, matrix cancer center, consisting of the seven academic institutions and teaching hospitals in the Harvard system. Bringing together seven institutions with a strong history of competition was challenging. However, there was a strong sense of institutional readiness to engage in this activity, and a genuine interest in the scientific progress that could be made through cross-institutional and cross-disciplinary research.

Each of the institutions brought both unique and overlapping disciplinary strengths. For example, the Dana-Farber had large efforts underway in basic and clinical science. However, its population-science group was strong but small, and could not meet the growing demands for collaboration. Bringing the Harvard School of Public Health and the Brigham and Women's Hospital—with significant strength in population studies—into the cancer center expanded the available expertise in this area and provided opportunities for new translational research endeavors, in bench-to-bedside translation as well as in efforts to reduce the gap between the evidence base and practice-in-community settings. As a result, population science emerged as a major strength in DF/HCC activities.

Cancer center leadership placed a heavy emphasis on creating "nodal points," or the intersection and development of interdisciplinary research projects between disease-based programs (e.g., breast, prostate) and the basic disciplines of cancer research (e.g., cancer biology, epidemiology). These nodal points have provided a key infrastructure for productive interdisciplinary interaction. Internal pilot funds are available only for projects that create new nodal points. The review teams represent all disciplines, and include scientists with experience in transdisciplinary approaches. The approach has spawned new collaborations across a range of disciplines. For example, a recently funded project examines the role of vitamin D as a contributor to colorectal and prostate cancer disparities. A team consisting of behavioral scientists, disease-based scientists, and epidemiologists are collaborating to look at vitamin D supplementation and uptake on disease markers among blacks. This study looks at the multiple levels of influence on colorectal cancer risk, and holds considerable promise for informing future cancer-prevention trials that seek to reduce racial disparities in cancer outcomes. This work would not have been likely had the DF/HCC not provided the initial opportunities for dialogue among these investigators and the pilot funding that led to other sources of support.

The organizational structure of the DF/HCC provided fresh opportunities for the development of a transdisciplinary approach. The leadership group includes representation from each of the disciplinary areas (e.g., population, clinical, and basic science), as well as from each of the institutional partners, and each of its members has a vote on key operational and budgetary matters. Because of the size of the DF/HCC (>1000 members in seven institutions spread across the city of Boston), there are significant barriers to collaboration in terms of geographic dispersion. So far this issue has been addressed by a commitment to regular meeting times and rotating meeting locations. That said, the lack of geographic proximity can provide a barrier because it prevents day-to-day, routine, unplanned, informal interactions, and may have implications for the design of interdisciplinary centers versus discipline-bound departments.

To facilitate cross-institutional collaboration, a common, centerwide administrative infrastructure was created. Regular meetings with institutional administrative representatives were designed to facilitate communication and streamline DF/HCC processes. Although progress has been made, many challenges remain. A particularly vexing problem is the fact that the partner institutions are separate fiscal entities, and thus require subcontracts for joint grant applications. This can sometimes discourage investigators from engaging in cross-institutional collaboration. However, one significant advance has been the creation of a single IRB that reviews all cancer-related protocols from the partner institutions. This greatly reduces the burden on investigators related to multiple IRB submissions resulting from cross-institutional collaborations.

When this effort is evaluated against the features of effective transdisciplinary collaborations identified by Ruddy and Rhee,[12] it is clear that there has been significant institutional support, careful team selection to support strong interdisciplinary interactions, the elucidation of common goals that help to operationalize transdisciplinary metrics, and multidirectional communication. However, the common metric for assessing the DF/HCC's success at creating transdisciplinary approaches has been the development of new funding, including program projects and large center grants. This remains less than ideal as a metric for assessing the impact of the cancer center's approach to fostering interdisciplinary research, as not all collaborations have the same level of interdisciplinary science. Other metrics are needed to truly measure the impact of this approach. Further, the question can be raised whether the transdisciplinary collaborations that have occurred are a function of the DF/HCC or would have occurred without it. Quite possibly some transdisciplinary partnerships would have developed out of mutual interest and openness to different disciplinary perspectives. However, in such a large setting, with >1000 cancer center members, there are many barriers to collaboration that the DF/HCC infrastructure can overcome. Further, in some parts of the university there is an emphasis placed on single-disciplinary approaches as the path to promotion. Because the DF/HCC provides a sanctioned setting in which researchers can consider the contribution of approaches outside of their individual areas, it has thus has made major contributions to changing the norms of collaboration throughout the system.

The *YourCancerRisk* Index

The Harvard Center for Cancer Prevention brought together clinicians, epidemiologists, behavioral scientists, and decision scientists to perform collaborative research, to train the next generation of leaders in cancer prevention, and to build communication platforms for bringing prevention messages to the public. The first major collaborative efforts focused on summarizing the causes[5] and prevention[13] of cancer and developing a series of tools that might help communicate the message that many forms of cancer are preventable. As colon cancer is largely preventable[14] and the relevant content was well-developed, this served as a useful starting point for bringing together epidemiologists, behavioral scientists, and risk-communication scientists.[15] The Harvard Colorectal Cancer Risk Assessment and Communication Tool for Research (HCCRACT-R)[15,16] was an interactive, computer-based tool used to provide individuals with their estimated personal risk for colorectal cancer, and can be used as a tool to study different risk-communication strategies. The risk-estimate calculation[16] was based on extensive review of scientific evidence and expert consensus on cancer-risk factors. It took into account both risk factors that are not modifiable (e.g., family history) as well as behavioral and lifestyle factors that can be changed to reduce risk (e.g., screening, physical activity, diet). The computer-based technology allowed developers to tailor the risk-communication messages based on the patient's risk profile. Details on the development and validation of the tool are provided elsewhere.[16]

The look, features, and functionality of the website were all influenced by transdisciplinary collaboration. For example, the original plans for the tool called for a paper-and-pencil measure, based on the epidemiologists' assumption that most people could accurately complete the basic math needed to compute one's risk score. Formative research conducted by the behavioral scientists demonstrated that there was a high level of error, and thus the team worked together to develop the website, whose design integrated principles from multiple disciplines. Over time, the HCCRAT-R research tool was expanded into the *YourCancerRisk* website, through the collaboration of colleagues in health communication, behavioral science, and epidemiology. Ultimately, the site was further expanded into *YourDiseaseRisk*, which provides risk assessment and information across a broad range of diseases (www.yourdiseaserisk.wustl.edu/). Later modules were added that address factors at multiple levels of influence, such as intrapersonal- and community-level factors. The site has received numerous awards for its content and continues to receive almost 2000 unique visitor sessions per day, with an average visit time of 8 minutes (Figure 1).

To date, evaluation of the tool has focused on risk perception and planned behavior change.[17–19] A broader evaluation will be required to assess the full impact of the transdisciplinary design team on the value of the overall integrated risk-assessment tool. Evaluation within a health plan that uses computerized medical records may offer a valuable setting for formal evaluation and the assessment of cost effectiveness.

Transdisciplinary Initiatives in Community Settings

The challenges in conducting community-based transdisciplinary research are many, although somewhat different from university-based research. The issue for communities engaging in scientific research is not disciplinary in nature (as *disciplinary* is typically thought of) but instead relates to power and resource distribution as well as to the knowledge of local culture, needs, and preferences. A key consideration when extending a transdisciplinary approach from the university setting to the community is whether the community has expertise at many levels and does not just represent a site in which research can be conducted. Thus, the community is, in essence, a contributing discipline that needs

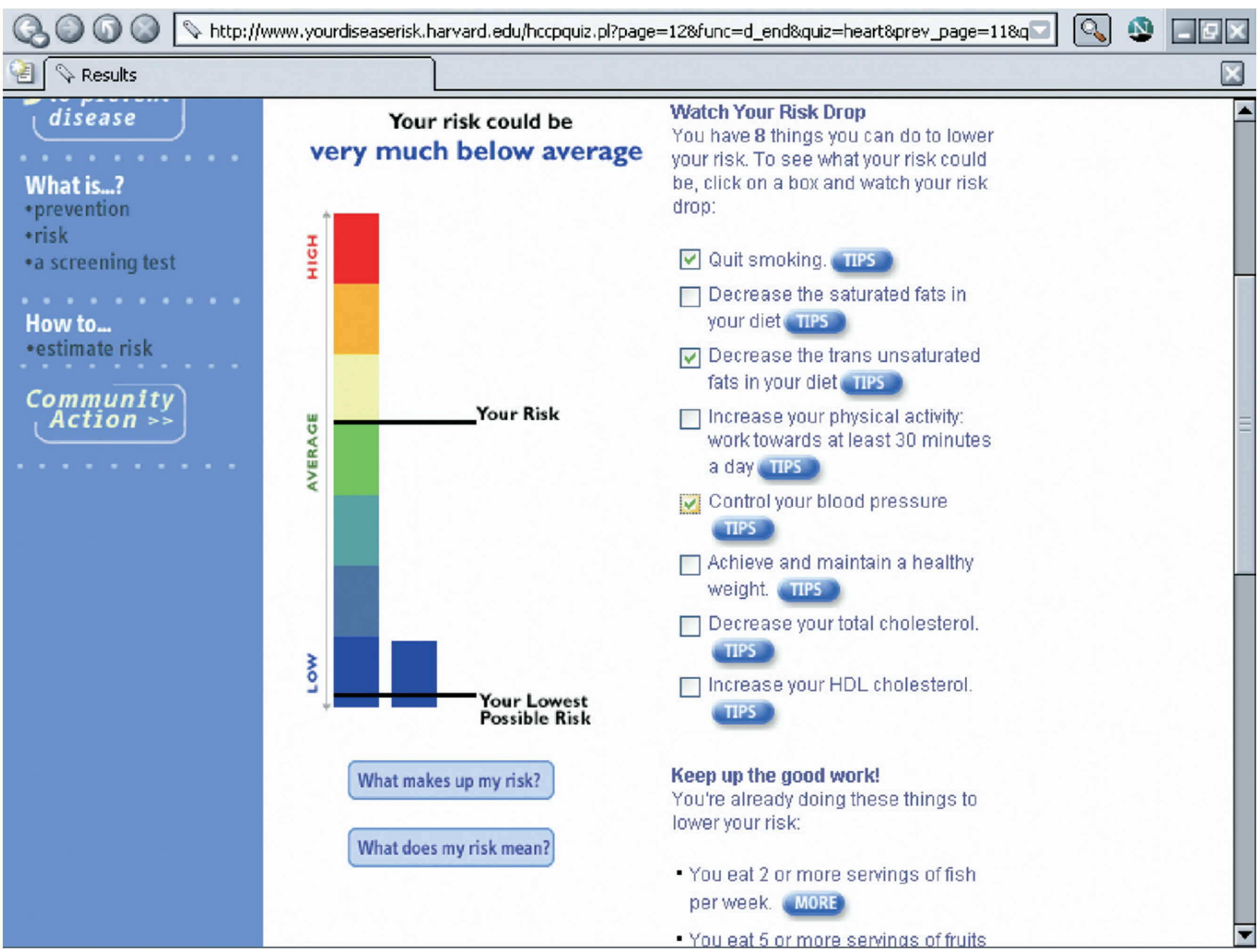


Figure 1. Sample screenshot from the *YourDiseaseRisk* website (www.yourdiseaserisk.wustl.edu/)

to be integrated into all aspects of project development. Institutional barriers often arise, most notably between the organizational and financial structures of university- and community-based organizations. Universities are intimately familiar with the federal research-funding system and know how to take the best advantage of federal research resources. Community organizations, however, are often at a disadvantage because they lack a research or fiscal infrastructure with an in-depth understanding of this system. Universities are also accustomed to having the bulk of a grant's budget go to their expenses; understandably, community groups are increasingly dissatisfied with this situation, or with being asked to "donate" their time and resources for research. Time is another dimension on which there are different cultures in university and community settings. University researchers are accustomed to the long lag-time between developing a research idea, obtaining funding for it, and being able to implement it; researchers are also accustomed to conducting large studies that typically take years to complete. Community members, on the other hand, often agree to be involved in research in order to address key community concerns that they want addressed in a timely manner. There are clearly differentials in timelines, expectations, and resources that can make community-based research collaborations very difficult.

Fortunately, there has been considerable emphasis on trying to develop models for effective collaboration between academic and community partners. The community-based participatory research approach developed by Barbara Israel and colleagues[20] exemplifies the importance of developing shared expectations, shared operating principles, and shared language in the context of academic–community partnerships. Four key principles of effective community-based participatory research partnerships that relate to transdisciplinary science stand out: (1) build on strengths and resources within the community, and understand that all participants have significant contributions to make; (2) integrate knowledge and action for the mutual benefit of all partners, so that the academic partners are not the only ones benefiting from the data being collected; it is crucial to recognize that knowledge is power, and all parties must share equally in that power; (3) promote a co-learning and empowering process that recognizes that all participants have the opportunity to learn from each other, and that the sharing of knowledge and empowerment strengthens the entire team; and (4) facilitate the collaborative, equitable involvement of all partners in all phases of the research. To the authors' knowledge, there has been little research investigating community readiness to engage in transdisciplinary science. However, if these principles are embraced, then the collaboration will by its nature spur transdisciplinary thinking, because of the emphasis on the integration of knowledge, co-learning, and empowerment. For example, Israel's work,[21] which focused on community-based participatory research approaches to asthma, has resulted in novel approaches to asthma management. High-level engagement of the community in intervention design and evaluation made it possible to broaden definitions of health and well-being beyond the individual and beyond health behaviors and health services and to understand health as produced within a social context.

The Massachusetts Community Network for Cancer Education, Research, and Training

The Massachusetts Community Network for Cancer Education, Research, and Training MassCONECT is another example of a transdisciplinary collaboration in a community setting that draws on principles of community-based participatory research. This effort unites behavioral scientists, epidemiologists, social epidemiologists, demographers, economists, and healthcare professionals with key community coalitions in three urban, low-income Massachusetts communities to advance cancer education, community-based participatory research, training, and cancer-control services. The particular focus of MassCONECT is on policy and clinical-service delivery to reduce cancer disparities in impoverished communities. It draws on sources of community strengths and assets through collaboration with existing community coalitions. Through the development of shared principles of engagement and collaboration, recognition is given to the value of all the areas of expertise represented, including all coalition members.

Further, a process for access to pilot funds has been developed that prioritizes interdisciplinary work and collaboration across coalitions, thus providing incentives for developing cross-disciplinary understanding and acceptance. Moreover, two of the pilot projects funded in the first year have emerged from interactions among scientists from different disciplines (social epidemiology and demography, and communication science) to map health disparities in the community and then to communicate the disparities through the media to influence public opinion about these disparities. Although a hands-off approach (e.g., maps produced by the social epidemiologist are then given to the communication scientists for working with the community) would be possible and perhaps easier, opportunities to integrate new learning from community perspectives into the current and future products would be limited.

New pilot projects emanate from the recent passage of legislation to mandate universal health-insurance coverage for all Massachusetts residents. The participating communities are enthusiastic that this reform may lead to better healthcare coverage and, ultimately, to better health outcomes among low-income communities. However, all recognize the need to be vigilant to determine the impact of this legislation, and have been extremely concerned that federal programs for providing cancer-screening services for low-income populations are now at risk. Therefore, a partnership has formed that encompasses a MassCONECT community coalition; two community health centers; and academic researchers representing health policy, health communication, and healthcare delivery to examine the impact of the legislation on health outcomes from a variety of perspectives. This project gives the community a critical voice in the evaluation of a key public policy that is intended to provide a benefit that to date is unproven. The community's role, particularly from the service-delivery perspective, has already shaped the evaluation in ways that would not have resulted had a purely academic team addressed this problem.

It is too early to tell if MassCONECT will lead to a transdisciplinary approach in either science or in the delivery of healthcare services, but this is a goal of the effort. It is crucial that evaluation metrics be developed to gauge both a community's readiness to participate in transdisciplinary science and whether the community can reap adequate benefits from such collaboration.

The Role of Translation/Dissemination in Transdisciplinary Approaches

The long-term goal of any health-related research endeavor should ultimately be to improve the human condition by reducing disease risk and prevalence and improving the quality of life. It is imperative that these research findings about cancer-risk reduction be translated to community-based settings that have the potential to affect population health. Transdisciplinary approaches have great potential to speed the rate at which research can contribute to the understanding and improvement of health. Unfortunately, to date there has been relatively little adoption of evidence-based practices,[22–26] and, as a result, the potential of risk-reduction efforts for cancer prevention have been largely unrealized. Unless careful attention is paid to this issue, innovations that occur as a result of transdisciplinary approaches are likely to have the same fate.

A recent call for more focus on dissemination research[27,28] will help increase the adoption of best practices. However, there is very little research focused in this area, particularly in community settings and with underserved populations. The failure to understand infrastructure barriers to both program dissemination and to design interventions that can be adopted in a wide variety of community, public health, and clinical practice settings may contribute to the difficulty of broadly disseminating effective interventions. Combined with a limited research base to inform dissemination practice, the uneven adoption of evidence-based interventions to promote health and prevent disease can contribute to increasing health disparities.[29] Dissemination and implementation research can help answer the common question of how to take a program or intervention that was tested and proven effective in one population and disseminate it successfully into another population. In light of limited resources, there have been warnings that the slow integration of evidence-based interventions into the community will continue unless a specific focus on dissemination research is undertaken.[26] It is imperative that transdisciplinary research teams, from their inception, think about translation and dissemination, so that innovations that are sustainable, feasible in community settings, and potentially influential on population health can be realized. In particular, there is a need for new conceptual models to bridge the existing gaps in translational research, particularly related to efforts to reduce the evidence-to-practice gap.[26,29,30]

One outstanding example of a dissemination tool that is a product of many disciplines is the Cancer Control PLANET (Plan, Link, Act, Network with Evidence-based Tools). PLANET is a web-based portal (http://cancercontrolplanet.cancer.gov/index.html) developed by and jointly sponsored by the NCI, the CDC, the Agency for Healthcare Research and Quality, and the American Cancer Society. The portal is designed to provide evidence-based cancer control programs to program planners, program staff, and researchers, thus enhancing their access to tested interventions and relevant data for program planning. PLANET includes state cancer profiles, a guide to community preventive services, research-tested interventions, and planning guides. The website's content results from the work of dozens of intervention researchers, statisticians, geographers, and informaticians, and demonstrates how the synergy of work in several disciplines can be used to develop a tool for the dissemination for cancer control.

Summary

Transdisciplinary approaches are a key part of efforts to address vexing public health problems and to achieve effective and durable translation. However, transdisciplinary approaches require a systematic and thoughtful process in which transdisciplinarity is valued and supported (monetarily and otherwise) by leadership, and through which barriers are minimized. Although there is currently much rhetoric in academic circles about transdisciplinary approaches, it is much easier to talk about these approaches than to implement them in a meaningful way. Careful attention to implementation is needed if transdisciplinary approaches are to fulfill their potential.

No financial disclosures were reported by the authors of this paper.

References

1. Emmons KM. Paper contribution F: behavioral and social science contributions to the health of adults in the U.S. In: Smedley BD, Syme LS, eds. Promoting health: intervention strategies from social and behavioral research. Washington DC: National Academy Press, 2000.
2. Hankinson S, Colditz G, Manson JE, Speizer F. Healthy women, healthy lives: a guide to preventing disease, from the Landmark Nurses' Health Study. New York: Simon and Schuster, 2001.
3. Sorensen G, Emmons K, Hunt MK, et al. Model for incorporating social context in health behavior interventions: applications for cancer prevention for working-class, multiethnic populations. Prev Med 2003; 37:188–97.
4. Tosteson AN, Weinstein MC, Hunink MG, et al. Cost-effectiveness of populationwide educational approaches to reduce serum cholesterol levels. Circ 1997;95:24–30.
5. Colditz GA, DeJong W, Hunter DJ, Trichopoulos D, Willett WC, eds. Harvard report on cancer prevention supplement. Volume 1: causes of human cancer. Cancer Causes Control 1996;7(1S):1–59.
6. Willett W, Colditz G, Mueller N. Strategies for minimizing cancer risk. Sci Am 1996;275:58.
7. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
8. Stokols D. Establishing and maintaining health environments. Toward a social ecology of health promotion. Am Psychol 1992;47:6–22.
9. Orleans CT. The behavior change consortium: expanding the boundaries and impact of health behavior change research. Ann Behav Med 2005;29(S):76–9.
10. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006; 33:515–31.
11. Kaplan GA, Everson SA, Lynch JW. The contribution of social and behavioral research to an understanding of the distribution of disease: a multilevel approach. In: Smedley BD, Syme SL, eds. Promoting health: intervention strategies from social and behavioral research. Washington DC: National Academy Press, 2000.
12. Ruddy G, Rhee K. Transdisciplinary teams in primary care for the underserved: a literature review. J Health Care Poor Underserved 2005;16:248–56.
13. Colditz G, DeJong D, Emmons K, Hunter D, Mueller N, Sorensen G, eds. Harvard report on cancer prevention: volume 2: prevention of human cancer. Cancer Causes Control 1997;8(1S).
14. Platz E, Willett W, Colditz G, Rimm E, Spiegelman D, Giovannucci E. Proportion of colon cancer risk that might be preventable in a cohort of middle-aged U.S. men. Cancer Causes Control 2000;11:579–88.
15. Emmons K, Koch-Weser S, Atwood K, Conboy L, Rudd R, Colditz G. A qualitative evaluation of the Harvard cancer risk index. J Health Commun 1999;4:181–93.
16. Colditz G, Atwood K, Emmons K, et al. Harvard report on cancer prevention: volume 4: Harvard cancer risk index. Risk Index Working Group, Harvard Center for Cancer Prevention. Cancer Causes Control 2000;11:477–88.
17. Waters E, Weinstein N, Colditz G, Emmons K. Formats for improving risk communication in medical tradeoff decisions. J Health Commun 2006;11:167–82.
18. Waters E, Weinstein N, Colditz G, Emmons K. Reducing aversion to side effects in preventive medical treatment decisions. J Exp Psychol Appl 2007;13:11–21.
19. Emmons K, Wong M, Puleo E, Weinstein N, Fletcher R, Colditz G. Tailored computer-based cancer risk communication: correcting colorectal cancer risk. J Health Commun 2004;9:127–41.
20. Israel BA, Schultz AJ, Parker EA, Becker AB. Review of community based research: assessing partnership approaches to improve public health. Annu Rev Public Health 1998;19:173–202.
21. Israel BA, Schulz AJ, Estrada-Martinez L, et al. Engaging urban residents in assessing neighborhood environments and their implications for health. J Urban Health 2006;83:523–39.
22. National Cancer Institute of Canada (NCIC). The language and logic of research transfer—finding common ground. Final report to the NCIC Board from the Joint Working Group on Translational Research and Knowledge Integration of the Advisory Committee on Research and the Joint Advisory Committee for Cancer Control. Toronto Ontario, Canada: NCIC, 2006.
23. Marincola FM. Translational medicine: a two-way road. J Transl Med 2003;1:1.
24. Mankoff SP, Brander C, Ferrone S, Marincola FM. Lost in translation: obstacles to translational medicine. J Transl Med 2004;2:14.
25. Ellis P, Robinson P, Ciliska D, et al. A systematic review of studies evaluating diffusion and dissemination of selected cancer control interventions. Health Psychol 2005;24:488–500.
26. Kerner J, Rimer B, Emmons K. Introduction to the special section on dissemination: dissemination research and research dissemination: how can we close the gap? Health Psychol 2005;24:443–6.
27. Glasgow RE, Bull SS, Gillette C, Klesges LM, Dzewaltowski DA. Behavior change intervention research in healthcare settings: a review of recent reports with emphasis on external validity. Am J Prev Med 2002;23:62–9.
28. Estabrooks PA, Glasgow RE. Translating effective clinic-based physical activity interventions into practice. AM J Prev Med 2006;31(4S):S45–56.
29. Klesges LM, Estabrooks PA, Dzewaltowski DA, Bull SS, Glasgow RE. Beginning with the application in mind: designing and planning health behavior change interventions to enhance dissemination. Ann Behav Med 2005;29(1S):66–75.
30. Glasgow RE, Bull SS, Piette JD, Steiner JF. Interactive behavior change technology: a partial solution to the competing demands of primary care. Am J Prev Med 2004;27(2S):80–7.

Interdisciplinarity and Systems Science to Improve Population Health

A View from the NIH Office of Behavioral and Social Sciences Research

Patricia L. Mabry, PhD, Deborah H. Olster, PhD, Glen D. Morgan, PhD, David B. Abrams, PhD

Abstract: Fueled by the rapid pace of discovery, humankind's ability to understand the ultimate causes of preventable common disease burdens and to identify solutions is now reaching a revolutionary tipping point. Achieving optimal health and well-being for all members of society lies as much in the understanding of the factors identified by the behavioral, social, and public health sciences as by the biological ones. Accumulating advances in mathematical modeling, informatics, imaging, sensor technology, and communication tools have stimulated several converging trends in science: an emerging understanding of epigenomic regulation; dramatic successes in achieving population health-behavior changes; and improved scientific rigor in behavioral, social, and economic sciences. Fostering stronger interdisciplinary partnerships to bring together the behavioral–social–ecologic models of multilevel "causes of the causes" and the molecular, cellular, and, ultimately, physiological bases of health and disease will facilitate breakthroughs to improve the public's health.

The strategic vision of the Office of Behavioral and Social Sciences Research (OBSSR) at the National Institutes of Health (NIH) is rooted in a collaborative approach to addressing the complex and multidimensional issues that challenge the public's health. This paper describes OBSSR's four key programmatic directions (next-generation basic science, interdisciplinary research, systems science, and a problem-based focus for population impact) to illustrate how interdisciplinary and transdisciplinary perspectives can foster the vertical integration of research among biological, behavioral, social, and population levels of analysis over the lifespan and across generations. Interdisciplinary and multilevel approaches are critical both to the OBSSR's mission of integrating behavioral and social sciences more fully into the NIH scientific enterprise and to the overall NIH mission of utilizing science in the pursuit of fundamental knowledge about the nature and behavior of living systems and the application of that knowledge to extend healthy life and reduce the burdens of illness and disability.

(Am J Prev Med 2008;35(2S):S211–S224) © 2008 American Journal of Preventive Medicine

Introduction

The vision of the National Institutes of Health (NIH) Office of Behavioral and Social Sciences Research (OBSSR) presented here provides an overview of the increasing role that transdisciplinary science and systems science methods are playing in transforming the understanding of the causality of health and disease in order to improve population-wide well-being. OBSSR, situated in the Office of the Director of the NIH, is mandated to stimulate, integrate, and increase support for behavioral and social sciences research across the 27 institutes and centers that constitute the NIH. OBSSR's other responsibilities include disseminating behavioral and social sciences research findings and providing advice to and communicating with the NIH Director, the legislature, other government agencies, the research community, and the general public on matters regarding behavioral and social sciences research. OBSSR serves as the nexus for cross-cutting research on the role that behavioral and social factors play in the etiology, treatment, and prevention of disease and in the promotion of health and improved quality of life. Additional information about OBSSR can be found at the Office's homepage (obssr.od.nih.gov).

From the Office of Behavioral and Social Sciences Research, Office of the Director, NIH (Mabry, Olster, Abrams*), Bethesda; and the Tobacco Control Research Branch, Division of Cancer Control and Population Sciences, National Cancer Institute, NIH (Morgan), Rockville, Maryland.

*Affiliation at the time of research for this paper.

Address correspondence and reprint requests to: Patricia L. Mabry, PhD, Office of Behavioral and Social Sciences Research, 31 Center Drive, Building 31, Room B1-C19, Bethesda MD 20892. E-mail: mabryp@od.nih.gov.

doi:10.1016/j.amepre.2008.05.018

There is growing recognition that the solutions to the most vexing public health problems are likely to be those that embrace the behavioral and social sciences as key players. To address this recognition, in 2007 OBSSR adopted a new strategic prospectus[1] to guide future priorities in the behavioral and social sciences at NIH. At the core of OBSSR's vision is a vertical integration across the levels of scientific analysis, that is, a transdisciplinary integration of the biomedical paradigms of molecular and physiological causal mechanisms with the ecologic paradigms of multilevel (individual, group, community, societal, and global) "causes of the causes" of health and disease.[2,3]

A note on terminology: As described by Stokols et al.,[4]

> **Interdisciplinarity** is a more robust approach to scientific integration in the sense that team members not only combine or juxtapose concepts and methods drawn from their own different fields, but also work more intensively to integrate their divergent perspectives, even while remaining anchored in their own respective fields. **Transdisciplinarity** is a process in which team members representing different fields work together over extended periods to develop shared conceptual and methodologic frameworks that not only integrate but also transcend their respective disciplinary perspectives.

Rosenfield[5] suggests that the term *interdisciplinary* lies between *multidisciplinary* and *transdisciplinary* science, implying a continuum along which the terms lie. However, the terms *interdisciplinary* and *transdisciplinary* science are sometimes used interchangeably, both within and outside the NIH. In the short term, because much of the work described here by OBSSR involves moving from multidisciplinary to interdisciplinary science, the term *interdisciplinary* is used throughout most of this document. *Interdisciplinary* is also the most common term used in the NIH Roadmap for Medical Research.[6] A long-term goal of OBSSR is to facilitate a process for moving from interdisciplinary analyses to the deeper conceptual synthesis and transformative momentum promised by transdisciplinary science.

The Value of Behavioral and Social Sciences Research Knowledge and Practice for Improving Public Health

A great deal is known about the basic science of how to change individual and population behavior. The application of findings from behavioral and social sciences research already plays a significant role in safeguarding and improving the public's health. The following selected examples provide a starting point to illustrate the tremendous power of psychosocial factors alone and the value of basic and applied behavioral and social sciences research in informing and improving the public's health.

Population and biological sciences identified tobacco-use behavior as the primary cause of most lung cancers and a leading cause of many other diseases, including cardiovascular disease. Behavioral and social sciences research informed the smoking interventions (individual, community, and policy level) that have spurred a dramatic reduction in U.S. tobacco use since its peak in the 1960s. In fact, the past decade witnessed a decline in overall cancer death rates for the first time in a century,[7] driven largely by the dramatic reduction in male smoking rates, from 54.1% at their peak in 1965[8] to 23.9% today.[9] Within the relatively short time span of 40 years, more than 45.7 million Americans have stopped smoking.[9] This is arguably one of the most successful public health interventions in recorded history,[10,11] and it has reduced the burden of many other diseases and excess societal expense as well. Behavioral and social sciences research can take much of the credit for this. Such research also has been at the center of understanding the multiple determinants of smoking initiation and cessation. Findings from behavioral and social sciences research have informed a broad spectrum of approaches (e.g., policy, cessation and prevention programs, communication of the risks associated with tobacco use). Of these, policy interventions (e.g., smoking bans, cigarette taxes) have been found to be among the most effective strategies for reducing smoking prevalence. (For in-depth treatment of this topic, see *Ending the Tobacco Problem: A Blueprint for the Nation*.[12]) Because of behavioral and social sciences research, tobacco use has been changed on a massive scale despite the highly addictive nature of nicotine.

Another achievement of behavioral and social sciences research is the landmark NIH Diabetes Prevention Program (DPP), which showed that lifestyle changes (i.e., alterations in dietary intake and physical activity that led to a reduction in body weight) were nearly twice as effective as a common medication in reducing the risk of developing type 2 diabetes.[13] An interdisciplinary effort to harness the power of the DPP intervention trial, together with lessons learned from tobacco control (especially around policy interventions), could help reverse the obesity and type 2 diabetes epidemics sweeping the developed world, and perhaps do so in less time than it took to cut smoking prevalence in half.

Research in the behavioral and social sciences has also spawned great progress in the development of effective treatments for the mental illnesses and disorders that are the leading contributors to disability. Meta-analyses show that cognitive–behavioral therapy is effective for unipolar depression, generalized anxiety disorder, panic disorder with or without agoraphobia, social phobia, posttraumatic stress disorder, childhood depressive and anxiety disorders, marital distress, anger, childhood somatic disorders, and chronic pain.[14] Moreover, cognitive–behavioral therapy is superior to antidepressants in the treatment of adult depression.[14] Finally, while a combination of cognitive–behavioral therapy and fluoxetine has been shown to be equal to fluoxetine alone in alleviating moderate-to-severe depression in adolescents, adding cognitive–behavioral therapy improves the safety of the medication by reducing suicidal ideation and events.[15]

Another major public health success to which behavioral and social sciences research on decision making, drug abuse, and sexual behaviors has made a significant contribution is the mitigation of the spread of HIV/AIDS.[16,17] As people have reduced their frequency of risky behaviors and new medications have become available, new AIDS cases in the U.S. have been cut almost in half, from a peak in 1992 of over 78,000 to approximately 40,000/year since 1998.[18] The contributions from behavioral and social sciences research along with the development of effective pharmacotherapies have changed HIV from an imminent death sentence to a treatable, chronic disease. But for medications to be successful, they must be taken on a regular basis, and behavioral and social sciences research has contributed to significant, albeit modest, improvements in adherence.[19] An effective partnership between the behavioral and social sciences and the biomedical sciences is at the core of the progress being made in the fight against HIV/AIDS worldwide.

Given the powerful discoveries and successes of basic and applied behavioral and social sciences research—largely achieved within single disciplinary silos without the scientific breakthroughs of recent times—OBSSR's vision is cautiously optimistic. It reflects a recognition that a new era is dawning in the 21st Century, an era for prevention and for re-engineering the lifestyles and environments that have been created previously. Lifestyle behaviors, social and physical environments, and policy and economic incentives can indeed be changed. Advances in biology, especially emergent work on epigenomics; dramatic successes in achieving population behavior changes; and improved rigor in behavioral, social, economic and population sciences are continuing apace, due in part to advances in mathematical modeling, informatics, imaging, sensor technology, spatial coding, cyber-infrastructure, and communication tools. These trends facilitate the understanding of the causes of preventable chronic, common diseases and poor health outcomes, and enable the development of targeted solutions. Changes are in order in the behavioral, social, chemical, and physical environments that are much more user-friendly to the fixed-DNA sequences of human beings. The new tools and technologies and the potential for interdisciplinary and, ultimately, transdisciplinary vertical synthesis from cells to society (e.g., Glass and McAtee[20]) set the stage for OBSSR's strategic vision for the future of both basic and applied behavioral and social sciences research at NIH and elsewhere.

Overview of OBSSR's Strategic Vision at NIH

The vision of OBSSR, as articulated in the strategic prospectus, is to mobilize the biomedical, behavioral, social, and population science research communities as partners to solve the most pressing health challenges faced by society.[1] Such a transdisciplinary approach is called for because there is increasing awareness that the most daunting and intractable problems in public health are so because of their complexity, and that the failure to appreciate and adequately address this complexity is thwarting attempts to tackle these problems.[21] Indeed, the health and well-being of the whole population may be best conceptualized as a "systems" problem, occurring on a continuum over the human lifespan as well as across a variety of levels of analysis, ranging from the cellular and molecular to individual and interpersonal behaviors, to the community and society and to macro-socioeconomic and global levels (Figure 1).[22]

The OBSSR at NIH has historically embraced a biopsychosocial perspective on the causes and correlates of health and illness.[23,24] Extending the biopsychosocial model, Glass and McAtee[20] provide an even stronger rationale for OBSSR's taking an interdisicplinary and systems science perspective to improve understanding of the forces that determine optimal health promotion and prevention, reduced disease burden, and improved chronic disease management across the human lifespan and across generations.

Consistent with the Glass and McAtee model of problem conceptualization,[20] the OBSSR staff recognize that the health problems of the 21st Century are complex. Solving these problems not only demands a movement from interdisciplinarity to transdisciplinarity synthesis, but also dictates the methods needed for addressing them.[25,26] OBSSR's emphasis on systems science reflects this awareness.

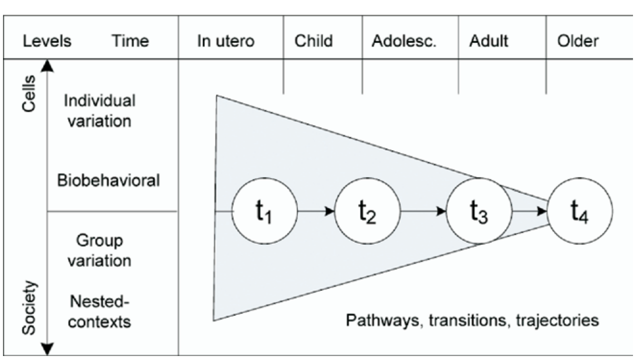


Figure 1. Transdisciplinary integration: from cells to society over time and across lifespan developmental phases
Reprinted with permission from Abrams[22]

The OBSSR's Strategic Prospectus

The strategic prospectus recently published by OBSSR[1] articulates four new programmatic directions, summarized below:

- Next-generation basic science: OBSSR will facilitate the next generation of basic behavioral and social sciences research informed by breakthroughs in complementary areas such as genetics, informatics, computer science, measures, methods, and multilevel analyses.
- Interdisciplinary research: OBSSR will facilitate collaborative research across the full range of disciplines and stakeholders necessary to fully elucidate the complex determinants of health and health-systems challenges. Such collaborations will yield new conceptual frameworks, methods, measures, and technologies that will speed the improvement of population health.
- Systems science approaches to health: OBSSR will stimulate research that integrates multiple levels of analysis in problem conceptualization and recognizes the complex and dynamic relationships among components of the system. These approaches are required to understand the ways in which individual, contextual, and organizational factors interact to determine health status.
- Population impact: OBSSR will work with its NIH partners to identify key issues in population health toward which scientists, practitioners, and decision makers can work together to accelerate the translation, dissemination, and implementation of the findings of BSSR in the service of improved health. This programmatic direction emphasizes a research agenda that is problem-focused and outcomes-oriented. It begins with a complex but clearly defined health problem and works backwards from the problem to identify the multiple causal pathways and feedback loops that will lead to development of the most powerful and efficient set of interventions to address the problem.

Interdisciplinarity is an explicit, programmatic theme within the OBSSR strategic prospectus that, in fact, pervades all other themes. A number of other cross-cutting themes also underlie OBSSR's programmatic directions. These themes include: (1) the elimination of health disparities[22]; (2) the strengthening of the science of dissemination (the quest for scientific evidence to determine the most effective ways to translate findings from basic research and clinical trials performed under ideal conditions to the successful widespread adoption and implementation by all target audiences and in national health policy)[27,28]; (3) capitalizing on recent advances in informatics, communications, imaging, sensor technology, and data-visualization techniques that aid data analysis and interpretation[29]; and (4) investigating commonality among theories and mechanisms of behavior change and sustained maintenance of change. Another goal of OBSSR is to enhance the interdisciplinary training of the current and next generation of behavioral and social scientists.

A critical milestone for enhancing interdisciplinary science and systems science is the rapid deployment of various components of cyber-infrastructure, making connectivity possible from the local to the global scale.[29,30] The National Science Foundation's landmark Atkins report[30] enumerates the potential and the critical base technologies underlying cyber-infrastructure, including the integrated electro-optical components of computation, storage, and communication that continue to advance in raw capacity at exponential rates. Above the cyber-infrastructure layer are the software programs, services, instruments, data, information, knowledge, and social practices applicable to specific projects, disciplines, and communities of practice. Between these two layers is the cyber-infrastructure layer of enabling hardware, algorithms, software, communications, institutions, and personnel. This layer should provide an effective and efficient platform for the empowerment of specific communities of researchers to innovate and eventually revolutionize what they do, how they do it, and who participates.

The next section elaborates on the programmatic directions outlined above, and includes specific research examples.

Programmatic Direction #1. Next-Generation Basic Science

Basic biomedical, behavioral, and social sciences research has produced enormous advances in understanding the factors that contribute to the risk of disease and to optimal health. Genetic studies in the 20th Century revealed mutations in individual genes responsible for a relatively small number of rare diseases, like Duchenne muscular dystrophy, cystic fibrosis, and sickle cell disease. The sequencing of the human genome and the completion of the HapMap have opened the door to genomewide association studies that will accelerate the identification of genetic contributions to health and disease. Simultaneously, advances in molecular and cellular biology, bioinformatics, and imaging are providing a rich, systems-biology view of cellular, organ, and organismal physiology, all of which will improve understanding of the etiology of disease and the ability to manage it.

At the same time, OBSSR recognizes that behavioral factors and social conditions have profound effects on the development and progression of common chronic diseases, premature disability, and mortality. Humans are both agents of change and affected by the process of change over time. This reciprocal determinism[31] is a dynamic process and is often nonlinear, multidetermined, and multilevel in nature. Patterns of behavior, exposures to pathogens, and the social and physical built environments are rapidly changing as a result of human agency. For example, tobacco use, diet, physical activity, obesity, and HIV/AIDS have all changed dramatically within the relatively short period of 1 or 2 decades during the 20th Century. Many changes in lifestyle and living conditions have had large impacts on subgroups of the population and on the absolute rates of disease burden within the whole population. On the positive side, from 1900 to 2004, the U.S. population witnessed a dramatic increase in life expectancy, from 47.3 years to 77.8 years, due primarily to changes in life circumstances and, more recently, due to improvements in health care.[32] On the negative side, between 1976 and 1980 and in 2003–2004, the prevalence of obesity—a risk factor for type 2 diabetes, heart disease, cancer, and other serious health problems—more than doubled in adults (from 13% to 34%) and in children aged 6–11 (from 7% to 19%), and more than tripled in adolescents (from 5% to 17%).[32] Moreover, persistent problems like tobacco use and disparities in health remain as leading causes of preventable disease burden, disability, and death.

An enormous scientific challenge now presents itself: What are the best ways to understand, prevent, and treat common, chronic diseases like heart disease, cancer, addiction, and mental illness when it is apparent that they are the result of interactions between individuals—in all their biological complexity—and their ever-changing physical, behavioral, and social environments? To maximally improve population health, the individual's genome and biology must be viewed in its much broader environment. Human genetic sequences are static, but the functional expression of that DNA sequence *is* influenced by the environment. To begin unraveling this complexity, NIH launched its Genes, Environment and Health initiative[33] and the Genetic Association Information Network.[34] These trans-NIH efforts seek to identify how gene–environment interactions contribute to common diseases by supporting genomewide association studies to link particular genetic variants to specific diseases and the development of environmental and biomarker-sensor technologies to measure behavioral and chemical exposures.

These activities are an excellent start, but significant challenges remain. The massive amounts of genetic and exposure data that will be collected will make sense only with improved basic behavioral and social sciences research, which can address questions such as these: *How should statistical power calculations and the interpretation of significant versus spurious associations be handled when so many variables can now be explored simultaneously? What is the best way to measure human phenotypes and the intermediate phenotypes that underlie complex clinical disease categories? What are the health-relevant physical, behavioral, and social environments, and how should these environmental exposures be measured over an entire lifespan? How can true gene–environment interactions be captured, and what are the mechanisms underlying these interactions?*[35] *How might environments be changed so that they foster, instead of assail, health?*

The above considerations, as well as others, have led OBSSR to the following research priority areas in next-generation basic behavioral and social sciences research:

Gene–environment interactions. How do genetic endowment and early-life experiences interact to determine physical and mental health later in life? How do behavioral, social, chemical, and physical environments cause epigenomic changes that, in turn, influence gene expression?

Environmental effects on physiology. How is psychosocial stress transduced into a biological signal that influences physiology? Can these findings be used to understand group behavior in the context of trauma such as natural or man-made disasters? Or can they be used to elucidate mechanisms underlying the deleterious effects of impoverished environments on health? How do large-scale societal structures (e.g., racial segregation, immigration and acculturation patterns, economic discrimination) affect physiology and, ultimately, health?

Technology, measurement, and methodology. How can the rapid establishment of cyber-infrastructure, grid computing, and recent advancements in computer sciences, informatics, imaging, networking, and knowledge management be harnessed to improve data collection and analysis? How can the development of new tools and methodologies be improved so that they measure more precisely and directly behavior and social environments in real time (e.g., ecologic momentary assessment, personal sensors, geospatial coding methods) and decipher multilevel pathways linking biology, behavior, environment, and societal trends?

Social integration and social capital. How do advances in technology and mobility affect neighborhood social networks and mechanisms such as resilience and connectedness? What is the impact of these advances on health behaviors?

Complex adaptive systems. How can the growing understanding of complex adaptive systems be used to better understand the process of decision making in health at the personal and systems levels?

Social movements and policy change. How do social movements related to health take shape and permit things like tobacco taxes, smoke-free workplace policies, and school lunch program changes to occur? How and why must public opinion change before legislative, regulatory, or other legal action is possible? What science will enable researchers to frame messages in ways that maximize the chances for motivating and sustaining positive, health-related change?

Investigators are beginning to address these questions. For example, Caspi and Moffitt[36] have been at the forefront of studies linking gene–environment interactions to psychiatric disorders in humans. Using data from the longitudinal Dunedin cohort study, they demonstrated that a particular, functional polymorphism in the promoter region of the serotonin transporter gene moderates the depressogenic influence of stressful life events during childhood. They reported that childhood maltreatment predicted adult depression only among individuals carrying the short allele genotype, but not among individuals carrying two copies of the long allele. Notably, the genotype did not predict adult depression.[37] These data illustrate that the social environment during childhood interacts with genetics to influence adult behavior and disease.

The biological pathways underlying gene–social environment interactions are being explored as well. Meaney, Szyf, and colleagues[38,39] have completed an elegant series of studies elucidating the mechanisms underlying the long-term effects of rat maternal behavior on the behavioral and neuroendocrine stress responses of their offspring. They have reported that a particular style of maternal behavior (low maternal rat-pup licking and arched-back nursing) during the first week of postnatal life leads to increased and prolonged reactivity of the hypothalamic–pituitary–adrenal (HPA) axis in the offspring. These changes are associated with reduced glucocorticoid receptor-gene expression in the hippocampi of the offspring, which appears to be due to epigenetic changes (increased DNA methylation, altered histone acetylation) in the promoter region of the glucocorticoid receptor gene. Central infusion of the histone deacetylase inhibitor, trichostatin A, to the offspring during adulthood reverses the previously defined differences in histone acetylation, DNA methylation, glucocorticoid-receptor expression, and HPA axis responses to stress, thus suggesting a causal relationship between patterns of maternal care and the epigenomic state, glucocorticoid-receptor expression, and stress responses in the offspring. While the extent to which these findings might generalize to other instances of behavioral and environmental programming remains to be determined, these findings do suggest that an epigenetic mechanism may underlie the transmission of intergenerational effects of a behavioral stimulus—one that is potentially reversible but can have dramatic downstream consequences (heightened neuroendocrine response to stress) across the offspring's lifetime.

Thus, there is enormous potential for greater understanding of gene–environment interactions and health through interdisciplinary partnerships among the behavioral and social sciences and the biomedical sciences as the field of epigenetics/epigenomics emerges. To support work at this leading edge of discovery, NIH has recently launched its NIH Roadmap Epigenomics Program[40] as part of the NIH Roadmap. Among the goals of the NIH Roadmap Epigenomics Program are the following: (1) to coordinate and develop a series of reference epigenome maps, analogous to genome maps, which will be publicly available to facilitate research in human health and disease; (2) to evaluate the epigenetic mechanisms in aging, development, environmental exposure (including physical and chemical exposures), behavioral and social environments, and modifiers of stress; and (3) to develop new technologies for the epigenetic analysis of single cells and the imaging of epigenetic activity in living organisms.

Programmatic Direction #2. Interdisciplinary Research

The staff at OBSSR recognize that solving the most pressing health problems will require a greater understanding of the full range of factors that determine health—biological, behavioral, social, and environmental—and of their complex interrelationships. In some instances, a single research discipline is best suited to tackle specific health problems. However, most common, serious, health problems cannot be adequately addressed solely within a single discipline, instead requiring a more comprehensive approach. New discoveries and innovative solutions may become possible when researchers in different disciplines meet at the interfaces and frontiers of those disciplines to pool their diverse bodies of knowledge. Interdisciplinary research and education are inspired by the drive to solve complex questions and problems, whether generated by scientific curiosity or by pressing social need. Over time, collaboration among diverse scientists may shift from multidisciplinary and interdisciplinary work to a full transdisciplinary synthesis that has the potential to produce new disciplines, as in psychoneuroimmunology, cognitive and social neurosciences, and behavioral genetics.

Research on stress and cancer is an excellent example of interdisciplinary research involving the behavioral and biomedical sciences. Antoni et al.[41] recently integrated a number of biomedical, behavioral, and clinical studies into a proposed mechanistic cascade underlying the links among behavior, biology, and cancer. Evidence is accumulating to suggest that stress, depression, and lack of social support influence the risk of cancer. For example, the breakup of a marriage has been associated with a twofold increase in the risk of breast cancer,[42] and long-term chronic depression appears to increase general cancer risks.[43,44] Basic research in physiology established a long time ago that the stress response is characterized by the activation of the sympatho-adrenal system, which releases the catecholamines, epinephrine, and norepinephrine, and the HPA axis, which releases glucocorticoids. More recently, animal models have shown that catecholamines, glucocorticoids, and other stress hormones influence multiple aspects of the tumor microenvironment, including: (1) the alteration of numerous aspects of immune function, (2) the promotion of tumor cell growth, (3) the migration and invasive capacity of cancer cells, (4) the stimulation of angiogenesis by the induction of pro-angiogenic cytokine production, and (5) the activation of oncogenic viruses (Figure 2).[41]

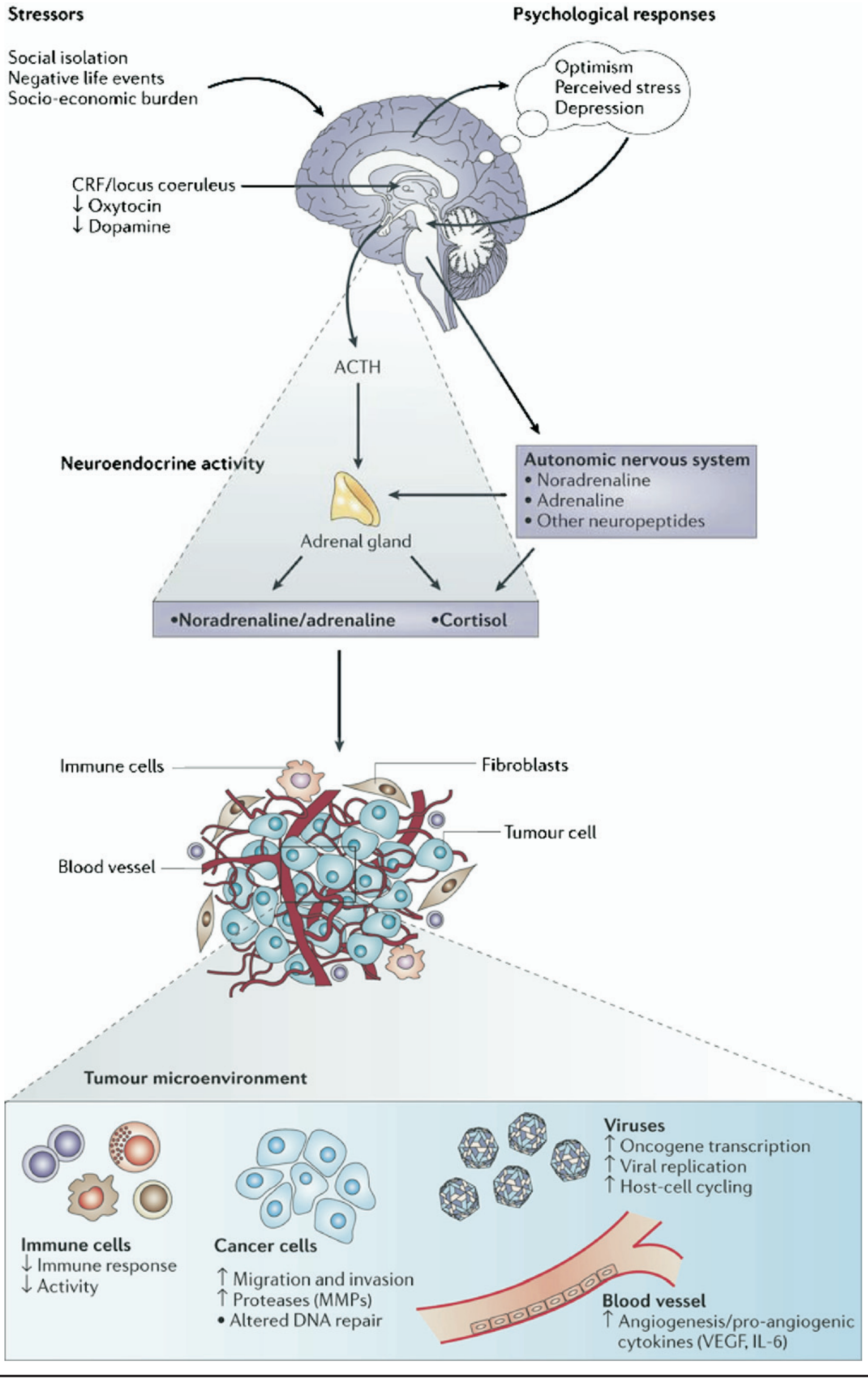


Figure 2. Effects of stress-associated factors on the tumor microenvironment
Reprinted with permission from Antoni et al.[41]

Moreover, recent studies have shown that the pharmacologic blockade of noradrenergic β receptors prevents the exacerbation of cancer that is otherwise observed following immobilization stress in mice, an indication that β-adrenergic signaling is critical in mediating the effects of stress on tumor growth in this model.[45] Some comparable data in humans are beginning to emerge. For example, it has been demonstrated that norepinephrine upregulates vascular endothelial growth factor, which, in turn, stimulates angiogenesis in two human ovarian cancer cell lines.[46] This catecholamine also increases human colon cancer–cell migration, and both epinephrine and norepinephrine promote the invasion of ovarian cancer cells in vitro. Taken together, data such as these indicate that a complex matrix of psychological, social, and biological factors in cancer, ranging from social isolation to viral infection, affects known physiological processes that influence cancer progression. Continued research in this area may yield targeted interventions to influence behavior, biology, or both to reduce the burden of cancer.

Programmatic Direction #3. Systems Science and Health

The term *systems science* is used here to refer to bringing to problem solving a perspective in which the problem space is conceptualized as a system of interrelated component parts (i.e., the "big picture"). This term was chosen in lieu of several others that may be synonymous, such as *systems thinking* or *complexity*, because some terms are associated with a particular "brand" of thought, and the authors feel that *systems science* is neutral while also inclusive. The system is viewed as a coherent whole, while the relationships among the components are also recognized and seen as critical to the system, for they give rise to the emergent properties of the system. *Emergent properties* are those properties that can only be seen at the system level and are not attributes of the individual components themselves (e.g., a flock emerges when a group of birds flies together; it is a property of the system, not of any individual bird). Systems science offers insights into the nature of the whole system that often cannot be gained by studying the component parts in isolation. Moreover, in a systems approach, there is recognition that embedded in the system are feedback loops, stocks and flows, that change over time (i.e., dynamic, nonlinear, complexity of the system).

The advantages of utilizing systems science as a complementary method for addressing complex problems include the fact that nonlinear relationships, the unintended effects of intervening in the system, and time-delayed effects are often missed with traditional reductionist approaches, whereas systems approaches excel at detecting these. The common conceptual orientation that defines a systems approach can be summarized as follows:

> a paradigm or perspective that considers connections among different components, plans for the implications of their interaction, and requires transdisciplinary thinking as well as active engagement of those who have a stake in the outcome to govern the course of change.[25]

Systems science is not a single discipline; rather, it is a linkage of disciplines to bring about problem understanding and solving under the paradigm described above.

Systems science does not refer to a single methodology; rather, it encompasses a wide range of methods and tools (e.g., system dynamics simulation, agent-based modeling, network analysis, Markov modeling, soft-systems analysis, discrete-event modeling). While technology is used to maximize the effectiveness of systems approaches, systems science is not a technology. For an in-depth introduction to this topic, readers are encouraged to view webcasts of the 2007 Symposia Series on Systems Science and Health.[47]

By embracing systems science, the research community will be better equipped to handle the policy-resistant problems that abound in public health. *Policy resistance* refers to the "tendency for interventions to be defeated by the system's response to the intervention itself." [21] In the last decades of the 20th Century, almost in parallel to the developments that spawned systems biology, the social–ecologic model emerged as a dominant world view in searching for explanations of the broader population-level causes of the very same common, chronic diseases that are the focus of biomedicine today.[48–51]

Other troubling causes of poor health and shortened life expectancy, such as access to care and disparities and inequality in healthcare delivery, have also been studied. The population, behavioral, and social sciences advanced beyond single discipline and simple causal views toward another valid systems view of understanding health and disease. In this world view, human behavior can be broadly defined as hierarchically organized along levels of complexity, from individual behavior to collective behavioral patterns within groups to higher levels of the clustering of patterns of behavior that are embodied in neighborhoods, worksites, schools, communities, cultural, ethnic, or religious affiliations, to even broader patterns determined by societal norms, financial incentives, and policies. These higher-order levels of factors interact in complex, dynamic, and multifactorial ways to produce the so-called "causes of the causes" of the complex common, chronic diseases.[2] In this ecologic perspective, the view of the ultimate "causes of the causes" lies as much in the behavioral–social–ecologic environment as it does in the proximal biological environment evident through reductionist approaches.

The implication of these disparate world views of causation (biomedical and ecologic) calls for a broader integration of the disciplines than has occurred to date. OBSSR's view is that there should be a "macro" integration of the three broad disciplinary domains: the largely biomedical sciences, the largely individual behavioral sciences, and the largely group or population-level sciences of the ecologic world view.

Recently there has been a call for a new integrative vision among the behavioral, social, and public health sciences that might loosely be termed *systems sociobehavioral science*, *systems medicine*, or, as one author has put it, *populomics*.[52] This is being called *vertical* integration, that is, integration *across* rather than *within* the three broad domains (i.e., the biomedical; the individual behavioral [intra-individual variation]; and the population [inter-individual or cluster variation] levels) of systems structure.[20] The hope is that this type of vertical synthesis across varying levels of analysis will lead to a next generation of science enabling further breakthroughs in the understanding and reduction of the burden and suffering of the major common, chronic diseases that afflict the U.S., other developed nations, and, increasingly, the developing nations. OBSSR's call for systems science is a call for an increasingly global perspective on the interaction, connectivity, and relationships within and across nations. The specific objectives for OBSSR with regard to systems science are:

- To facilitate the development and application of the conceptual frameworks and tools needed for the application of systems methodologies to problems of health and its determinants;
- To promote and support the development of informatics tools to facilitate the collaboration and dissemination of data relevant to the behavioral, population, and social sciences (e.g., longitudinal epigenetic, biomarker, social, and behavioral data related to health);
- To contribute to the development of analytical frameworks, methods, and algorithms capable of integrating, analyzing, and interpreting highly diverse data with varying metrics from research on genomic sequences, molecules, behavior, and social systems;
- To collaborate in the development of the curricula, modules, and materials required to train health scientists in the application of systems science; and
- To encourage the application of systems-organizing principles among stakeholder organizations in behavioral and social sciences research, and to promote the development of systems-organizing expertise among leaders, policymakers, and researchers.

Bringing systems science to bear on public health problems has the potential to explain how small changes at the individual level accumulate at the population level to reveal significant shifts in the absolute causes of disease.[2,3] System dynamics modeling and agent-based models are methods that can simulate the complex relationships among the components of a system and emergent behavior—that is, behavior that is observed at the bird's-eye vantage point of the system emerging from the behavior of the individual components of the system (e.g., blood clotting and scab formation emerge at the systems level from the behavior of individual cells). Because of its unique ability to consider simultaneously both the whole system and its individual parts, systems science is capable of producing solutions that take into account a broad range of factors pertinent to the problem under consideration; for instance, genetic-to-environmental–, cellular-to-behavioral–, and biological-to-social–systems approaches have proven extremely valuable when applied to problems identified in a variety of disciplines, including defense,[53] business,[54] and cellular biology.[55,56] Systems science shows promise for unlocking the secrets of complex, multidimensional health issues and for transforming this knowledge into effective interventions that can fundamentally change population health.[57]

An example of applying systems science to public health problems is illustrated by Jones et al.,[58] who used system dynamics simulation modeling to explain type 2 diabetes prevalence since 1980 and to predict possible futures through 2050. The conceptual model (Figure 3) divided the U.S. population into those who do not have diabetes (normal glycemic levels); those at high risk for developing type 2 diabetes (i.e., people with prediabetes, divided into diagnosed and undiagnosed); and those who meet diagnostic criteria for type 2 diabetes (diagnosed and undiagnosed, subdivided into with and without medical complications from diabetes). The conceptual model included births (entry into the system); deaths (exit from the system); and individual members' movements among the diagnostic categories over time (stocks and flows), as well as numerous factors contributing to diabetes outcomes (e.g., clinical management of diabetes, self-monitoring, healthy-lifestyle adoption, and medication use).

The relationships among all of these variables were quantified and the model was calibrated and validated in an iterative process using historical data from a variety of sources (e.g., the U.S. Census Bureau, the National Health Interview Survey, the National Health and Nutrition Examination Survey, and the Behavioral Risk Factor Surveillance System).

Simulations were then generated according to a variety of assumptions that were programmed into the model via algorithms. Figure 4 shows the results of the simulated population burden of diabetes (i.e., deaths) under various scenarios where an intervention is introduced that is designed to: (1) improve the clinical management of those diagnosed with diabetes; (2) improve pre-diabetes

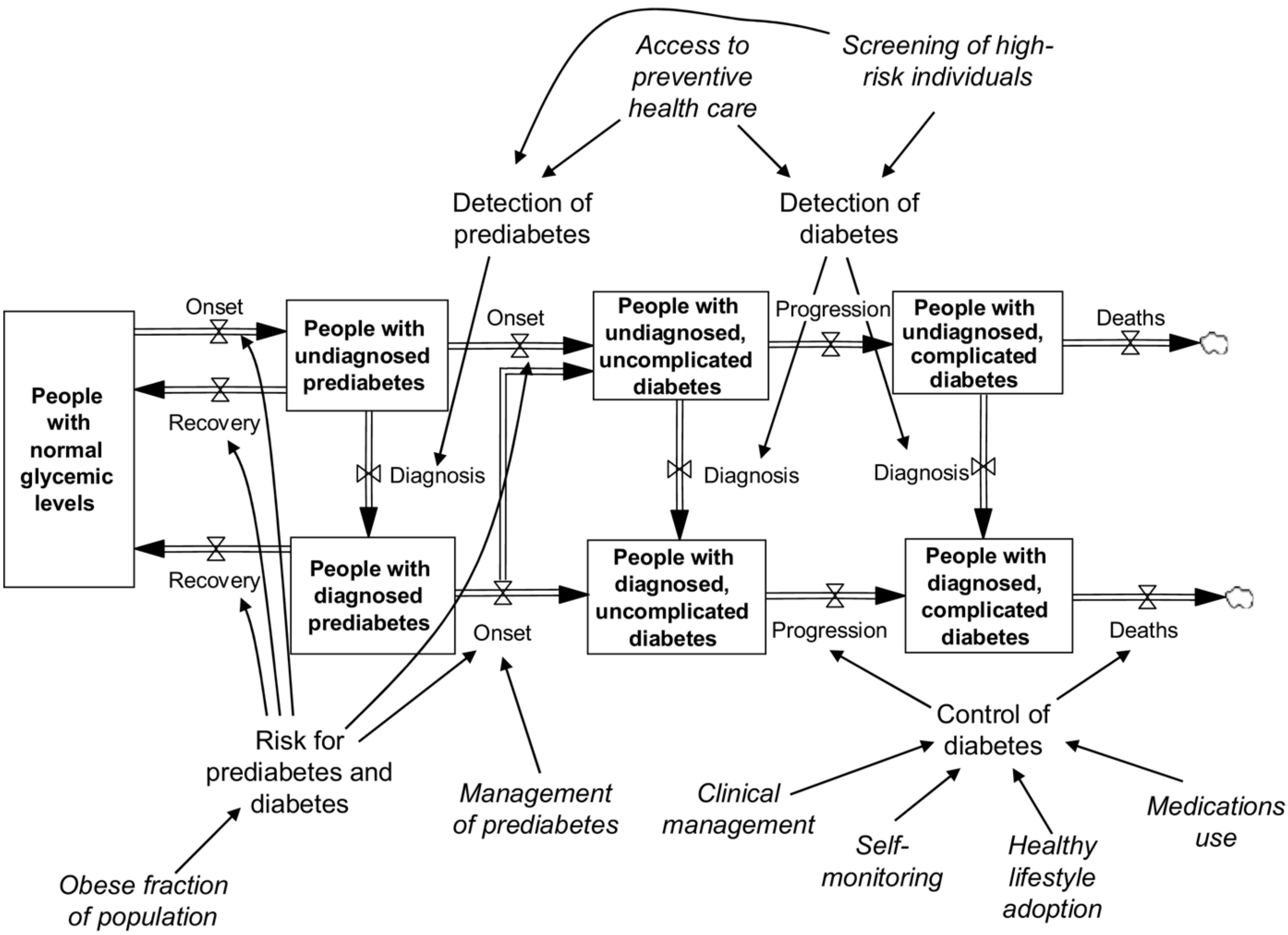


Figure 3. Diabetes conceptual model
Reprinted with permission from the American Public Health Association[58]

management; and (3) prevent diabetes (through the prevention of obesity). These three hypothetical scenarios are compared to "baseline," a predictive model in which the status quo of diabetes clinical practices and prevention activities is maintained at baseline levels.

The following outcomes were predicted under each of the three scenarios:

1. The improved clinical management of diabetes leads to short-term improvements in diabetes control, complications, and associated deaths. However, following these improvements in the first few years, there is a rapid rise in complication deaths. Improvements in complications are rapidly overtaken by the growth in diabetes prevalence because nothing has been done to reduce diabetes onset.
2. Efforts to manage persons with prediabetes would lead to reductions in the onset of diabetes initially, and ultimately would reduce deaths from diabetes complications. But without prediabetes prevention efforts, the amount of reduction in deaths is less than optimal.
3. Finally, the primary prevention of diabetes shows the most drastic and lasting reductions in deaths.

However, even this powerful step alone (i.e., reducing rates of obesity without concurrent changes in prediabetes management or clinical diabetes management) would not reduce the overall burden of diabetes in terms of both the number of unhealthy days (not pictured) and the number of deaths due to diabetes right away (Figure 4). In fact, the number of deaths attributable to diabetes would actually rise through at least the year 2020, although during subsequent decades, a significant decrease in diabetes prevalence and deaths would occur. Thus, the time perspective is vital to determining the value of a strategy—that is, disease management works in the short term, but primary prevention is more effective in the long term. This example illustrates the potential of systems science to inform healthcare and policy decisions to improve population health.

In another example of adopting a systems approach to improving the understanding of a public health problem, Levy and colleagues developed SimSmoke,[59] a simulation model for guiding policy to make a population impact on reducing smoking prevalence. SimSmoke uses historical and current data to model

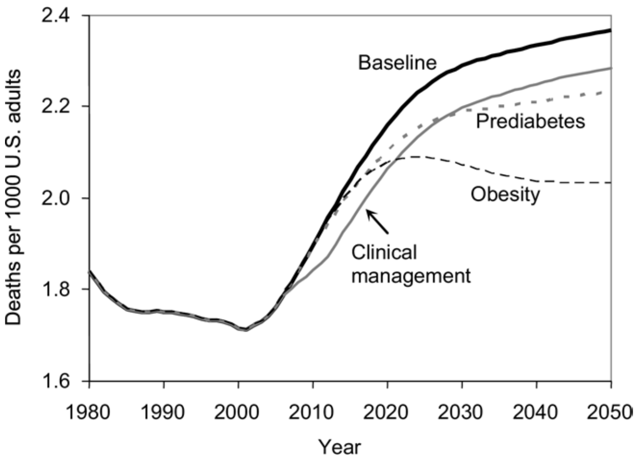


Figure 4. Model output for three intervention scenarios compared with the baseline scenario for diabetes complication-related deaths
Reprinted with permission from the American Public Health Association[59]

the multiple sources and complex interrelationships that determine tobacco-use prevalence and its health effects. A discrete-time dynamic model was developed that simulated smoking prevalence and tobacco-related deaths over a 40-year period. The model employed a first-order Markov process that modeled population growth and age-based rates of tobacco initiation, cessation, and relapse. This model simulated the impact of five policy-level interventions on smoking prevalence: taxes, clean indoor-air laws, strategies to reduce youth access to cigarettes, strategies to promote cessation treatments, and mass-media policies. Researchers used empirical and predicted data for the effects of each of these areas on model parameters. SimSmoke showed the relative contributions made by a variety of different policy interventions (i.e., increasing cigarette prices, introducing smoking bans, introducing media campaigns to encourage cessation and prevention, implementing additional restrictions on youth access to tobacco, and introducing proactive quitlines) toward the desired outcomes (i.e., reduction in smoking prevalence and reduction in deaths attributable to tobacco). Such models can be used to inform decisions about how best to allocate financial resources and formulate policies to optimize a desired public health impact. The focus is on making an efficient population impact to address a complex societal problem (tobacco-use behavior) with an emphasis on outcomes and on multiple causal pathways, feedback loops, and control-systems dynamics that underlie the way the tobacco industry and the public health constituencies vie for their respective goals.

The above examples illustrate the potential for systems science to radically transform the behavioral, social, and population sciences to a degree similar in magnitude to the transformation that systems biology and bioinformatics are now bringing about in biology. This sentiment is captured in the broad vision for cyber-infrastructure outlined in the Atkins report of the National Science Foundation[30]:

> The opportunity is here to create cyberinfrastructure that enables more ubiquitous, comprehensive knowledge environments that become functionally complete for specific research communities in terms of people, data, information, tools, and instruments and that include unprecedented capacity for computational, storage, and communication . . . . They can serve individuals, teams and organizations in ways that revolutionize what they can do, how they do it, and who participates.

Programmatic Direction #4. Population Impact

The North Karelia Project[60] underscores the value of a multimodal, problem-based approach to a major public health issue. In the 1960s, Finnish men had the world's highest rate of heart disease mortality. The death rate was especially high in the province of North Karelia, a rural area in the eastern part of Finland. In 1972 officials in North Karelia began a community-based initiative to reduce cardiovascular disease and mortality. The North Karelia project included: (1) cultural interventions addressing traditional Finnish dietary norms to reduce fat intake and to double the consumption of fruits and vegetables; (2) media outreach, including health-related news features, educational content, and a national "quit and win" contest; (3) the training of healthcare providers to provide cardiovascular risk-factor assessment and counseling for all patients; (4) the engagement of community leaders and workplaces to spearhead health-promotional activities; and (5) policy interventions that included public smoking bans, the elimination of tobacco advertising, and taxes earmarked for tobacco control programs.

A variety of research disciplines, including social psychology, nutrition science, marketing, education, primary care medicine, policy, and tobacco control were brought together to design this multilevel intervention. The results were impressive: By the early 2000s, the number of deaths of working-age Finnish men from coronary heart disease had plummeted 75%. In North Karelia, the effects were even more pronounced (an 82% reduction in deaths), and life expectancy for men increased 7 years. Much of this reduction in mortality came from reductions in risk factors like high blood pressure, high cholesterol, and smoking, because of nutritional changes and smoking cessation. Today, this project continues to sustain itself with a modest level of public resources.

Another problem with tremendous population impact is that of health disparities. If this problem were widely addressed, enormous benefit could be conferred on those affected by these inequalities. Transdisciplinary and systems science perspectives may be valuable approaches for addressing health disparities and inequality.[22] These approaches permit researchers in the field to step back and consider the ways that their science has been framed by historical, disciplinary perspectives (i.e., a focus on intra-individual, molecular, genetic "causes" within biomedical frames of reference versus a focus on the socioeconomic forces and the levels of socio-environmental context, such as social position and poverty, as the "causes of the causes" within ecologic frameworks). For example, a recent study used county-level geospatial and racial-group coding to categorize into clusters the population of the U.S. according to expected longevity; these clusters are called the "Eight Americas."[61] An incredible gap of 35 years of life expectancy was reported between the highest and lowest life-expectancy ranks among the eight clusters. The lowest cluster is grouped among nations of the world with the lowest life expectancy (sub-Saharan Africa and Russia) and can be viewed as excluded from the gains made in average life expectancy in the U.S. during the entire 20th Century. Life expectancy in the cluster at the high end of the Eight Americas exceeds that of nations whose life expectancy is the highest in the world (3 years better than Japan for females and 4 years better than Iceland for males).

Abrams[22] suggests a new framework for integrating historically disparate frames of reference from individual and population sciences into a new synthesis. This framework would embrace a model of genes and the social and physical environments in a complex, nonlinear, reciprocal interaction of risk and protective factors, over the lifespan and across generations.[2,20,39,62] Interdisciplinary research and systems science can perhaps clarify the extent to which gene–environment interactions account for racial and ethnic health disparities and improve the development of effective interventions and policies to eliminate those disparities.[63]

These brief examples are but a few of an increasing number of approaches that use a problem-focused, outcomes-oriented goal to strengthen the science of dissemination, implementation, and policy research. The hope is that a deeper understanding of the basic mechanisms in complex adaptive systems will help to improve the design of the next generation of interventions and lead to better (i.e., informed by science) health policies. Such approaches use the tools of basic and applied interdisciplinary science; systems science; and problem-focused, outcomes-oriented strategies to maximize their public health impact.

New Directions at NIH in Support of Interdisciplinary, Translational, and Systems Sciences

Although OBSSR does not have grant-making authority, it partners with NIH institutes and centers to develop research initiatives, alternately playing a lead or participatory role. Since 2003, OBSSR has led the development of a number of trans-NIH initiatives under the auspices of the NIH Roadmap. The three themes of the NIH Roadmap are New Pathways to Discovery, Research Teams of the Future, and Re-Engineering the Clinical Research Enterprise.

Interdisciplinary research, one of the components of the Research Teams of the Future theme, has included several initiatives specifically targeting the behavioral and social sciences. The OBSSR-led initiatives Supplements for Methodological Innovations in the Behavioral and Social Sciences (RFA RM-04-013)[64] and Meetings and Networks for Methodological Development in Interdisciplinary Research (RFA RM-04-014)[65] supported research on dietary intake, physical activity, child development, stress–immune interactions, environmental exposures, treatment decision making, patient quality of life, gene–environment interactions, pain, and aging. Seven postdoctoral institutional-training grants were awarded under another NIH Roadmap initiative, Interdisciplinary Health Research Training: Behavior, Environment and Biology (RFA RM-05-010).[66] These programs provide formal coursework and research training in a new interdisciplinary field for individuals holding advanced degrees in a different discipline. The Exploratory Centers for Interdisciplinary Research (RFA RM-04-004)[67] program is supporting the centers that are investigating cognition, elder self-neglect, or youth vulnerability to sexually transmitted infections and unintended pregnancies. Another center focuses on the pathways through which the environment, genetic, and psychosocial domains jointly shape child health and well-being. A 2007 initiative, Facilitating Interdisciplinary Research via Methodological and Technological Innovation in the Behavioral and Social Sciences (RFA RM-07-004),[68] supports the development of new and innovative measures, methods, and technologies that underlie the interdisciplinary integration of human social science, behavioral science, or both, with other disciplines across varying levels of analysis. Links to descriptions of the projects funded under these and other interdisciplinary NIH Roadmap initiatives can be found on the NIH Roadmap website (www.nihroadmap.nih.gov/interdisciplinary/fundedresearch.asp).

Finally, one of the initiatives developed under the Re-Engineering the Clinical Research Enterprise theme is the Institutional Clinical and Translational Science Award (CTSA; RFA RM-08-002).[69] CTSAs are cooperative agreements to provide resources and develop methodologies to overcome blocks at both the discovery (translation between bench and bedside) and implementation (translation between bedside and practice and community) steps. Translational research has two components: (1) applying discoveries generated during research in the laboratory and in preclinical studies to the development of trials and other human studies, and (2) research aimed at enhancing the adoption of best practices in the community. This second component of translation, that is, the science of dissemination and implementation of best practices, requires strong behavioral and social sciences research.

Framework for the Future: Office of Portfolio Analysis and Strategic Initiatives (OPASI)

The NIH Roadmap is now administered by the Office of Portfolio Analysis and Strategic Initiatives[70] (OPASI), a new office within the Office of the Director of NIH. OPASI has several related missions, including the development of methods to help the agency analyze and manage its portfolio; the gathering and analysis of data on the public health burden to help set priorities; and the evaluation of the outcomes of NIH-funded activities. A major purpose of OPASI is to provide an incubator space, in the form of NIH Roadmap initiatives, to accelerate critical research efforts that address major, cross-cutting NIH priorities. The general intent of OPASI is consistent with the concept of systems science across NIH and the identification of new opportunities that cut across disciplines and across different levels (from cells to society) as well as the fostering of research that will reduce the public health burden—all of which is also consistent with the mission and vision of OBSSR.

Conclusion

The sciences concerned with optimal health, well-being, and disease management have revealed just how broad the future world view needs to be. At the end of the day, the simple, single-cause, single-discipline, and now, even single-level-of-analysis models—whether predominantly biomedical or predominantly behavioral or social–ecologic—are increasingly viewed as necessary but insufficient. This is especially true for the common, most preventable, and most expensive chronic diseases that afflict the vast majority of populations in the developed nations of the world and that cry out for research to provide a more timely understanding of basic mechanisms, better interventions, and more science-informed health policy. The biomedical, reductionist world view of the causes of disease and the behavioral, social–ecologic world view of the "causes of the causes" of disease are really two sides of the same coin that must be merged to develop a new synthesis and a more complete and useful heuristic framework to guide future research.

Systems science, cyber-infrastructure, and new technology may well provide the foundation stones to facilitate OBSSR's strategic vision: an integration of next-generation basic science with its applications to clinical practice, community dissemination, and health policy; a vertical integration from cells to society and a progression from interdisciplinary science to a deeper set of transdisciplinary conceptual syntheses; and an ability to examine nonlinear causal loops and solutions using backward engineering of the complex causal pathways, starting from a defined problem or pressing public health challenge (like eliminating health disparities; reversing the epidemics of obesity, sedentary lifestyle, and type 2 diabetes; and further reducing tobacco use and the incidence HIV/AIDS). In the final analysis, the mission of basic and applied science at OBSSR and across the NIH embraces a problem-focused, outcomes-oriented set of goals to make a timely and cost-efficient impact on improving the nation's health and reducing the absolute burden of disease and disability at the individual and population levels.

The authors would like to thank Bobby Milstein, PhD, at the CDC for his inspiration and education on systems science, which is reflected in this work. They are grateful for his unwavering support and partnership with OBSSR on systems science initiatives.

The authors would also like to thank the reviewers of the manuscript for this paper. While the reviewers are unknown, the authors believe the reveiwers' feedback helped strengthen this paper.

No financial disclosures were reported by the authors of this paper.

References

1. The Office of Behavioral and Social Sciences Research, NIH. The contributions of behavioral and social sciences research to improving the health of the nation: a prospectus for the future. 2007. http://obssr.od.nih.gov/Content/Strategic_Planning/Strategic+Plan_2007/ObssrIndex.htm.
2. McKinlay JB, Marceau LD. To boldly go . . . . Am J Public Health 2000;90:25–33.
3. Rose G. The strategy of preventive medicine. New York: Oxford University Press, 1992.
4. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
5. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
6. NIH. NIH roadmap for medical research. www.nihroadmap.nih.gov.
7. Thun MJ, Jemal A. How much of the decrease in cancer death rates in the U.S is attributable to reductions in tobacco smoking? Tob Control 2006;15:345–7.
8. National Centers for Health Statistics. National Health Interview Survey (NHIS). Hyattsville MD: CDC, 1965.
9. CDC. Cigarette smoking among adults—U.S., 2006. MMWR Morb Mortal Wkly Rep 2007;56:1157–61.
10. Warner KE. Effects of the antismoking campaign: an update. Am J Public Health 1989;79:144–51.
11. Warner KE. Tobacco policy research: insights and contributions to public health policy. In: Warner KE, ed. Tobacco control policy. San Francisco: Jossey-Bass, 2006.
12. IOM. Ending the tobacco problem: a blueprint for the nation. Washington DC: National Academies Press, 2007.
13. Knowler WC, Barrett-Connor E, Fowler SE, et al. Reduction in the incidence of type 2 diabetes with lifestyle intervention or metformin. N Engl J Med 2002;346:393–403.
14. Butler AC, Chapman JE, Forman EM, Beck AT. The empirical status of cognitive-behavioral therapy: a review of meta-analyses. Clin Psychol Rev 2006;26:17–31.

15. March JS, Silva S, Petrycki S, et al. The treatment for adolescents with depression study (TADS): long-term effectiveness and safety outcomes. Arch Gen Psychiatry 2007;64:1132–43. Erratum in: Arch Gen Psychiatry 2008;65:101.
16. CDC. Twenty-five years of HIV/AIDS—U.S., 1981–2006. MMWR Morb Mortal Wkly Rep 2006;55:585–9.
17. CDC. Evolution of HIV/AIDS prevention programs—U.S., 1981–2006. MMWR Morb Mortal Wkly Rep 2006;55:597–603.
18. CDC. Epidemiology of HIV/AIDS—United States, 1981–2005. MMWR Morb Mortal Wkly Rep 2006;55:589–92.
19. Haynes RB, Yao X, Degani A, Kripalani S, Garg A, McDonald HP. Interventions to enhance medication adherence. Cochrane Database Syst Rev 2005;(4):CD000011.
20. Glass TA, McAtee MJ. Behavioral science at the crossroads in public health: extending horizons, envisioning the future. Soc Sci Med 2006;62:1650–71.
21. Sterman J. Learning from evidence in a complex world. Am J Public Health 2006;96:505–14.
22. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006;33:515–31.
23. Anderson NB. Levels of analysis in health science: a framework for integrating sociobehavioral and biomedical research. In: McCann S, Lipton JM, eds. Annals of the New York Academy of Sciences. Vol. 840. New York: New York Academy of Sciences, 1998.
24. Kessel F, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science. New York: Oxford University Press, 2003.
25. Leischow S, Milstein B. Systems thinking and modeling for public health practice. Am J Public Health 2006;96:403–4.
26. Homer JB, Hirsch GB. System dynamics modeling for public health: background and opportunities. Am J Public Health 2006;96:452–8.
27. Glasgow R, Green L, Klesges L, et al. External validity: we need to do more. Ann Behav Med 2006;31:105–8.
28. Kerner J, Rimer B, Emmons K. Introduction to the special section on dissemination: dissemination research and research dissemination: how can we close the gap? Health Psychol 2005;24:443–6.
29. Bertenthal B. Cyberinfrastructure for the social and behavioral sciences. Psychological Science Agenda 2005;19:2–4.
30. Atkins DE, Droegemeier KK, Feldman SI, et al. Revolutionizing science and engineering through cyberinfrastructure: report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure. Washington DC: National Science Foundation, 2003.
31. Bandura A. Social foundations of thought and action: a social-cognitive theory. Upper Saddle River NJ: Prentice-Hall, 1986.
32. National Center for Health Statistics. Health, U.S., 2006. With chartbook on trends in the health of Americans. Hyattsville MD: The Center, 2006.
33. NIH, The genes, environment and health initiative (GEI). www.gei.nih.gov/index.asp.
34. NIH. Genetic association information network (GAIN). www.genome.gov/19518664.
35. Committee on Assessing Interactions Among Social, Behavioral, and Genetic Factors in Health. Hernandez LM, Blazer DG, eds. Genes, behavior, and the social environment: moving beyond the nature/nurture debate. Washington DC: National Academies Press, 2006. www.nap.edu/catalog/11693.html.
36. Caspi A, Moffitt TE. Gene-environment interactions in psychiatry: joining forces with neuroscience. Nat Rev Neurosci 2006;7:583–90.
37. Caspi A, Sugden K, Moffitt TE. Influence of life stress on depression: moderation by a polymorphism in the 5-HTT gene. Science 2003;301:386–9.
38. Meaney MJ, Szyf M. Environmental programming of stress responses through DNA methylation: life at the interface between a dynamic environment and a fixed genome. Dialogues Clin Neurosci 2005;7:103–23.
39. Szyf M, Weaver IC, Champagne FA, Diorio J, Meaney MJ. Maternal programming of steroid receptor expression and phenotype through DNA methylation in the rat. Front Neuroendocrinol 2005;26(3–4):139–62.
40. NIH. NIH roadmap for medical research: epigenomics: an overview. nihroadmap.nih.gov/epigenomics.
41. Antoni MH, Lutgendorf SK, Cole SW, et al. The influence of bio-behavioural factors on tumour biology: pathways and mechanisms. Nature 2006;6:240–8.
42. Lillberg K, Verkasalo PK, Kaprio J, Teppo L, Helenius H, Koskenvuo M. Stressful life events and risk of breast cancer in 10,808 women: a cohort study. Am J Epidemiol 2003;157:415–23.
43. Reiche EM, Nunes SO, Morimoto HK. Stress, depression, the immune system, and cancer. Lancet Oncology 2004;5:617–25.
44. Spiegel D, Giese-Davis J. Depression and cancer: mechanisms and disease progression. Biol Psychiatry 2003;54:269–82.
45. Thaker PH, Han LY, Kamat AA, et al. Chronic stress promotes tumor growth and angiogenesis in a mouse model of ovarian carcinoma. Nature Medicine 2006;12:939–44.
46. Lutgendorf SK, Cole S, Costanzo E, et al. Stress-related mediators stimulate vascular endothelial growth factor secretion by two ovarian cancer cell lines. Clin Cancer Res 2003;9:4514–21.
47. NIH. Office of Behavioral and Social Sciences Research. 2007 symposia series on systems science and health. obssr.od.nih.gov/Content/Lectures+and+Seminars/Systems_Symposia_Series/SEMINARS.htm.
48. Cohen DA, Scribner RA, Farley TA. A structural model of health behavior: a pragmatic approach to explain and influence health behaviors at the population level. Prev Med 2000;30:146–54.
49. McLeroy KR, Bibeau D, Steckler A, Glanz K. An ecological perspective on health promotion programs. Health Educ Q 1988;15:351–77.
50. Stokols D. Establishing and maintaining healthy environments. Toward a social ecology of health promotion. Am Psychol 1992;47:6–22.
51. Green LW, Richard L, Potvin L. Ecological foundations of health promotion. Am J Health Promot 1996;10:270–81.
52. Gibbons MC. A historical overview of health disparities and the potential of eHealth solutions. J Med Internet Res 2005;7:e50.
53. Krygiel AJ. Behind the wizard's curtain: an integration environment for a system of systems. Washington DC: National Defense University Press, 1999.
54. Senge PM. The fifth discipline: the art and practice of the learning organization. New York: Doubleday Dell Publishing Group, Inc., 1994.
55. Weston AD, Hood L. Systems biology, proteomics, and the future of health care: toward predictive, preventative, and personalized medicine. J Proteome Res 2004;3:179–96.
56. Grimm V, Revilla E, Berger U, et al. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 2005;310:987–91.
57. Trochim WM, Cabrera DA, Milstein B, Gallagher RS, Leischow SJ. Practical challenges of systems thinking and modeling in public health. Am J Public Health 2006;96:538–46.
58. Jones AP, Homer JB, Murphy DL, Essien JD, Milstein B, Seville DA. Understanding diabetes population dynamics through simulation modeling and experimentation. Am J Public Health 2006;96:488–94.
59. Levy DT, Ross H, Powell L, Bauer JE, Lee HR. The role of public policies in reducing smoking prevalence and deaths caused by smoking in Arizona: results from the Arizona tobacco policy simulation model. Public Health Manag Pract 2007;13:59–67.
60. Puska P. The North Karelia Project: 20 year results and experiences. Helsinki: National Public Health Institute, 1995.
61. Murray CJL, Kulkarni SC, Michaud C, et al. Eight Americas: investigating mortality disparities across races, counties, and race-counties in the U.S. PLoS Med 2006;3:e260. doi:10.1371/journal.pmed.0030260.
62. Krieger N, Chen JT, Waterman PD, Rehkopf DH, Subramanian SV. Painting a truer picture of U.S. socioeconomic and racial/ethnic health inequalities: the Public Health Disparities Geocoding Project. Am J Public Health 2005;95:312–23.
63. Anderson NB, Nickerson KJ. Genes, race, and psychology in the genome era: an introduction. Am Psychol 2005;60:5–8.
64. NIH. Supplements for methodological innovations in the behavioral and social sciences (RFA RM-04-013). grants.nih.gov/grants/guide/rfa-files/RFA-RM-04-013.html.
65. NIH. Meetings and networks for methodological development in interdisciplinary research (RFA RM-04-014). grants.nih.gov/grants/guide/rfa-files/RFA-RM-04-014.html.
66. NIH. Interdisciplinary health research training: behavior, environment and biology (RFA RM-05-010). grants.nih.gov/grants/guide/rfa-files/RFA-RM-05-010.html.
67. NIH. Exploratory centers for interdisciplinary research (RFA RM-04-004). grants.nih.gov/grants/guide/rfa-files/RFA-RM-04-004.html.
68. NIH. Facilitating interdisciplinary research via methodological and technological innovation in the behavioral and social sciences (RFA RM-07-004). grants.nih.gov/grants/guide/rfa-files/RFA-RM-07-004.html.
69. NIH. Institutional Clinical and Translational Science Award (CTSA; RFA RM-08-002). grants.nih.gov/grants/guide/rfa-files/RFA-RM-08-002.html.
70. Office of Portfolio Analysis and Strategic Initiatives. 2007. http://opasi.nih.gov.

Toward Transdisciplinary Research

Historical and Contemporary Perspectives

Frank Kessel, PhD, Patricia L. Rosenfield, PhD

Abstract: Over the past two decades a variety of national and international efforts has sought to bring together health and social scientists to address complex health issues. This paper reviews how the notion of transdisciplinary research has emerged; discusses research programs that have successfully traversed discipline boundaries in sustained fashion; considers facilitating and constraining factors that have emerged from the analyses of this process; and suggests next steps for conceptualizing, organizing, and assessing transdisciplinary research based on the notion of heterarchy.
(Am J Prev Med 2008;35(2S):S225–S234) © 2008 American Journal of Preventive Medicine

Introduction

Contemporary health and social scientists increasingly endorse research that crosses disciplinary lines. Health scientists often refer to social conditions in their research on disease-specific and system-related problems. Similarly, social scientists working on topics related to health at least give a nod toward epidemiology. Yet 50 years after the publication of Paul's path-breaking book[1] that pointed to the generative results of social scientists reaching out to address health problems, research that consistently and creatively crosses disciplinary, departmental, and faculty lines remains relatively difficult to initiate, fund, publish, and sustain.

In this paper we offer, first, a contribution to understanding the programmatic and scientific context in which the concept of transdisciplinary research linking the health and social sciences emerged as an attempt to move beyond conceptual and institutional inertia. The focus is on Rosenfield's 1992 paper[2] because it has served as an entry point for much of the current discussion of health research across disciplinary boundaries. We then consider ideas resulting from contemporary research programs that, consistent with that initial analysis, have successfully traversed discipline boundaries in sustained fashion and, in some instances, achieved levels of integrative creative collaboration. These considerations suggest the persistence of factors that constrain boundary-crossing inquiry but also findings that point to the rich promise of such integrative inquiry. Finally, we suggest possible next steps that may serve as a catalyst for promoting and guiding the conduct of transdisciplinary research.

From the University of New Mexico (Kessel), Albuquerque, New Mexico; and the Carnegie Corporation of New York (Rosenfield), New York, New York

Address correspondence and reprint requests to: Patricia L. Rosenfield, PhD, Carnegie Corporation of New York, 437 Madison Avenue, New York NY 10022. E-mail: plr@carnegie.org.

The Concept of Transdisciplinarity: Parallel Developments

World Health Organization

In the late 1970s, Patricia Rosenfield joined the WHO as the economist for the Tropical Disease Research (TDR) program and responsible for its Social and Economic Research (SER) Steering Committee. Even with supportive TDR leadership, she found a situation similar to what George Foster,[3] a pioneer in medical anthropology, later described as a challenge at WHO since its founding. The early (1947) commitment of those "far-sighted medical doctors and international health workers [who] began to realize that the effective delivery of health care, especially in cross-cultural settings, involved sociocultural as well as purely medical factors,"[3] was not being fully honored. For example, the medical staff would usually ask social scientists to provide manuals and develop questionnaires but not to identify the social and behavioral factors that might inform a deeper understanding of communities' health conditions. Foster also observed that the review process for research support at WHO entailed primarily medical doctors evaluating social science proposals. As a result, social scientists were only rarely full-fledged members of the health team.

The SER committee, however, had several advantages that enabled it to overcome the constraints noted by Foster. First, the TDR program was funded as an extra-budgetary program; several donors (notably from Scandinavian countries and the World Bank) insisted that social and economic factors be studied along with biomedical factors in the analysis of disease transmission and control. Also, the SER steering committee was composed primarily of social scientists charged with the

 doi:10.1016/j.amepre.2008.05.005

responsibility of reviewing and funding proposals submitted by teams of social and health scientists, ensuring knowledge of and respect for the social science aspects of proposals. Further, the committee was part of a larger biomedical program with equal standing to all the other committees (e.g., epidemiology, biomedical sciences, and several disease-specific groups). This structure constituted a considerable organizational advantage, providing access to WHO disease-control specialists and the health policy aspects of projects. It also facilitated collaboration with health ministries, national disease-control programs, public health institutes, and medical schools, as well as social science programs and other ministries.

In its early stages, the committee still faced some of the constraints noted by Foster,[3] notably problems of credibility and legitimacy within WHO.[2] Staff malariologists, for example, were convinced that they understood communities better than social scientists because they were in the field spraying mosquitoes after obtaining local permission. Other disease and vector-control specialists felt that adding social scientists to the team would waste time and money. Nevertheless, social scientists in developing countries were willing to engage in research with their counterparts in the health sciences and health ministries. Together they developed and implemented projects that won over many of the skeptics inside WHO, in ministries, and academic social science departments. As a result, interdisciplinary teams tackled such topics as knowledge of disease transmission, attitudes toward disease-control programs, and new methods focused, for example, on household instead of individual units of analysis. These teams produced results that helped communities and intervention programs reshape their approaches to disease control.[2]

Notwithstanding the success of this process, Rosenfield became concerned that cross-disciplinary work was becoming a fad within WHO, rather than a theoretically and methodologically sound approach for research leading to changes in the delivery of health care and disease control. In particular, terms such as *multidisciplinary* were often used without sustained attention to the fundamental question: *How can collaboration across disciplines lead to new ways of framing, understanding, and addressing human health issues?* Her concern was that superficial use, or even misuse, of such terms would lead to recommendations for changes in the design and delivery of health programs that could waste resources, dash raised expectations, and even eliminate the opportunity for effective partnerships between heath and social scientists.

Given this concern, Rosenfield decided to examine the meaning of *multidisciplinary* and *interdisciplinary* research as expressed by her health and biomedical counterparts. Reviewing projects supported by TDR, as well as programs outside of WHO such as the Applied Diarrheal Disease Research Program,[2] she concluded that the problems Foster[3] had identified persisted in the 1990s, and not just at WHO. What was called multidisciplinary or even interdisciplinary research involved primarily separate input of different disciplines, but **not** creative ways to blend those to yield deeper understanding of the problem or integrative solutions that would be both more acceptable to the population at risk and more cost-effective in the long run. This recognition—that terminology was fuzzy, leading to unmet expectations and limited usefulness of results that did not match some of the associated claims[a]—is what prompted her 1992 paper.[2,b] And as clearly conveyed by other papers in this supplement to the *American Journal of Preventive Medicine*, this analysis—both linguistic and conceptual—has helped stimulate a body of work aimed at further clarifying the distinctions between different forms of cross-disciplinary research and underlining the value-added contributions of using a transdisciplinary framework for both the analysis and solution of health problems.

Europe and the U.S.

Paradigmatic change was taking place elsewhere, both prior to and in parallel with the efforts at WHO. As early as 1970, writing about different forms of knowledge, Judge and Clark[5] had used the term *trans-disciplinary*. Through the 1970s and 1980s, several scholars in Europe and some in the U.S.—primarily from the areas of ecology, computers, and complexity analysis—began to consider the meaning and use of the concept of transdisciplinarity.[5,6]

Then, in the early 1990s, with an increasing recognition of complexity associated with globalization, the social science community in Europe began to consider the concept of transdisciplinarity.[7,8] In 1994 the First World Congress of Transdisciplinarity was held in Portugal and a charter of transdisciplinarity endorsed by the participants. Article 14 of the Charter, *inter alia*, is relevant for current discussions in the health field:

> *Rigor*, *openness*, and *tolerance* are the fundamental characteristics of the transdisciplinary attitude and vision. *Rigor* in argument, taking into account all existing data, is the best defense against possible distortions. *Openness* involves an acceptance of the unknown, the unexpected and the unforesee-

[a]On the persistent issue of fuzzy terminology, see our closing paragraph below and reference 4.

[b]It is encouraging to note that the SER work thrives in 2007 as an active part of the TDR Programme, funding research and training projects in the developing world. Moreover, at a recent TDR meeting, the Ghanaian Minister of Health, Major Courage Quashigah, noted the following: "There's nothing more powerful than an idea whose time has come . . . Although this meeting is focusing on health, the outcome is about how effectively we formulate policies that can help reduce the disease burden in developing countries. To do this, health research must increasingly have a social and ethno-cultural outlook." TDR NEWS, Special issue from Africa, October 2006, p. 4.

able. *Tolerance* implies acknowledging the right to ideas and truths opposed to our own.[7,8]

Since then, as Klein[9]—a leading analyst of transdisciplinary research approaches—elucidates, the domain has burgeoned, as signaled by annual prizes to recognize excellence in transdisciplinary research, the establishment of an Institute in Switzerland, a journal, and an increasingly active presence on the web.[10–12] Moreover, the Strategic Plan of the European Science Foundation for the period 2006–2010 mentions not only multidisciplinary and interdisciplinary research, but also refers to transdisciplinary work in the Humanities section, highlighting health and disease as a major theme.[13]

Finally, in 2006 Stokols extended the examination of transdisciplinary approaches to a level that includes attempted links between research and broader action.[14] Pooling multiple approaches from research and action in his comprehensive review, Stokols outlined "programmatic directions for the scientific study of transdisciplinary research and community action . . . to identify strategies for refining and sustaining future collaborations (and their intended outcomes) among researchers, community members and organizations."[14] Along with his other writings, Stokols' work clearly complements the analysis provided here and elsewhere.[15,c]

Extending the Concept: Illustrative Cases

Developing Countries

As a further notable development in the 1990s, the concept of transdisciplinary research across the health and social sciences was taking hold in the developing world. Spurred primarily by the innovative work at the University of Newcastle (Australia) under the leadership of Albrecht and Higginbotham, social and health scientists began to produce conceptual analyses and empirical findings in the area of transdisciplinary health research.[16–18] Higginbotham et al.[19] also took up the challenge to institutionalize the concepts underpinning transdisciplinarity and developed the first curriculum based on this approach, a curriculum still in use at Newcastle for programs in ecosystem health.[d]

In 2002 Higginbotham[20] and his colleagues published a book containing interdisciplinary case studies undertaken in 1990s. Each of the sections reviews the state of knowledge and action in a different region—Asia and the Pacific, Africa, and Latin America. Given the importance, if not uniqueness, of these analyses of health and social science collaboration throughout the developing world, they warrant in-depth study. Here, the emphasis is on only a few central points.

Social scientist Ramos-Jimenez[21] notes the wide range of health conditions in the Asia-Pacific region and the substantial number of scientists, nearly 1000, involved in health social science research. Nevertheless, she also underlines the challenges in crossing "rigid disciplinary boundaries," including the need for better training, material and demonstrations of the actual application of interdisciplinary and transdisciplinary research approaches. She points to effective cases of interdisciplinary research on chronic diseases, such as heart disease, and use of services that are helping to increase understanding and support for interdisciplinary research.

In Africa, sociologist Erinosho[22] notes the commitment of social scientists to work on health issues, but also observes that "a gulf between social and biomedical scientists remains because African biomedical scientists only grudgingly accommodate social scientists working within medical school[s] . . ."[22] Yet in some domains, such as work on traditional medicine and HIV/AIDS, there has been increasing collaboration around the issues of culture-bound programs and the use of ethnographic research. However, despite this critical mass of committed individuals in both regions (Africa and Asia–Pacific), familiar challenges abound, most notably in building and sustaining a sense of partnership across the disciplines and with practitioners and health service decision-makers.

In contrast, sociologist Briceno-Leon[23] observes that in Latin America there has been ". . . long felt appreciation of social issues shown by a number of the region's physicians and public health specialists . . . Many stressed in their writings and actions the importance of society, the environment and people's ways of living toward understanding health."[23] Recently, increased opportunities for collaboration of medical and social scientists have emerged at the community and policy level, especially around disease-specific concerns, so that "potential areas of work and encounter [across fields] have multiplied. The relationship between the social sciences and health is very diverse but also characterized by enormous theoretical wealth and reflection."[23]

Only one case study in the Higginbotham volume explicitly uses a transdisciplinary research framework. Applying the framework to assess the rational use of drugs programs in Indonesia, Hadiyono,[24] a clinical psychologist, describes the challenge of health and social scientists working together as equal partners.

[c]Recent initiatives reviewed in the Kessel and Rosenfield preface[15] include programs of the Canadian Institutes for Health Research that are strikingly consistent with Stokols' focus on community-oriented, action research.

[d]It should be noted that some of the Higginbotham et al.[19] initiatives were supported by Rosenfield after she joined Carnegie Corporation in 1987, with the encouragement of David Hamburg (then the Corporation President). But other foundations and agencies joined the effort, notably the Ford Foundation, the Rockefeller Foundation and the Canadian-based International Development and Research Center. Probably because electronic networking was not well developed, this collaboration took place separately from European efforts, as well as from NCI's leadership initiatives in the area of transdisciplinary research on tobacco.

Based on observations as her team moved through stages from multidisciplinary and interdisciplinary to transdisciplinary collaboration, this analysis of the process yields lessons for those committed to achieving a transdisciplinary research program—namely, the importance of team members':

- willingness to commit sufficient time to such collaborative endeavors,
- openness to learning each other's disciplinary languages and jargon,
- capacity to build mutual confidence and trust, including with community members and practitioners, and
- overcoming the challenge of working as equals, with no knowledge or discipline or practice assuming priority.

Consistent with Stokols' writing cited above, Hadiyono concludes by noting that these studies also brought practitioners and community members together as active participants in the process.

Reviewing their illuminating case studies, Johnson and colleagues[25] underline challenges and opportunities encountered by social and health scientists who seek to cross discipline boundaries, suggesting that such factors are at work in both developed and developing countries. These include:

- the difficulties of defining roles for team members—scientists and researchers, community members and health services personnel—to enable complementary learning and blending expertise and skills at different stages of the research and application process;
- the need to avoid defining the problem either in a narrow, reductive way or so broadly that it becomes practically uninterpretable; and
- the need to overcome discipline rigidity and hyperspecialization as barriers to theoretical and methodologic innovation.

Finally, Johnson and colleagues[25] conclude that, despite such challenges, the promise of transdisciplinary research flows from the recognition that "health social science becomes most effective when the group engaged with the problem adopts transdisciplinary thinking. That is, they transcend disciplinary bounds to synthesize knowledge about the problem in the quest to understand it fully as a complex dynamic system."[25]

The U.S. and the United Kingdom

The National Cancer Institute (NCI)'s 2006 Conference on the Science of Team Science that stimulated this article was a turning point in building understanding and acceptance of the need for transdisciplinary research in health. It is not a coincidence that NCI provided sponsorship. There is ample evidence that NIH support for scientific innovations has been indispensable in promoting and sustaining research collaboration across the health and social sciences.

As only one example, the volume edited by Frank Kessel et al.[26] was supported by the NIH Office of Behavioral and Social Science Research (OBSSR); and several of its case studies illustrated creativity in NIH funding mechanisms, notably at the National Institute of Aging (NIA). NIH was not the only important institutional catalyst, however. Around 1980 the MacArthur Foundation began supporting research networks aimed at establishing connections across disparate research areas, disciplines and universities. And several universities, such as Duke, Wisconsin, and the University of California at San Francisco (UCSF) were early leaders in encouraging interdisciplinary or transdisciplinary initiatives (although not explicitly under such rubrics).

In the 5 years since the Kessel et al.[26] collection of case studies was published, the boundary-crossing trend has not only continued, but also become stronger. The revised edition[27] documents, most significantly, that each of the research teams has been able to stay together and even expand around the core of their research efforts, despite occasional changes in leadership and membership.

One reason for such continuity is sustained funding from foundations and government (in the U.S. and UK), as well as from researchers' home universities. A complementary explanation could be that sustained funding comes about because of the intellectual depth the teams are bringing to understanding problems, along with the significance of their findings and solutions in the field. In other words, like the transdisciplinary tobacco-oriented work funded by NCI, such research programs have at least the potential to make a positive difference in academia, health programs, and households.

Two noteworthy examples of this trend are the case studies prepared by Olshansky and Carnes,[28] and Ryff and Singer.[29] Olshansky and Carnes note that "in the demographic and population sciences, NIH promoted the development of interdisciplinary science by soliciting planning centers through the P20 mechanism (research program project grants) as a way to encourage research consortia to develop new interdisciplinary approaches to solving complex important biomedical research problems."[28] Their own area of biodemography has benefited from this support. Olshansky and Carnes also predict that, as a result of NIH acceptance of multiple investigators, there will be fewer "penalties imposed by promotion and tenure committees on individuals who participate in collaborative activities." Their conclusion: "It is change at NIH that ultimately drives the perceptions and generates a support for interdisciplinary collaboration at universities and departments, not the other way around."[28]

Similarly, in their chapter Postscript, Ryff and Singer[29] observe that obstacles to conducting cross-boundary work, especially those relating to funding and peer-review publications, appear to be weakening. As an important example, NIA has awarded their team a sizable grant to study the biological, psychological and social pathways to positive and not-so-positive health. This will entail a follow-up of their earlier MIDUS (Midlife in the U.S.) work, originally with support from the MacArthur Foundation. They note that "the initial study . . . has become a major forum for publishing 'integrative studies' that cross disciplinary lines in an effort to understand age-related variation in health and well-being."[29] The new NIA P01 program support has enabled the addition of a longitudinal survey as well as biomarkers. Concerned about therapy and applications of their findings, Ryff and Singer are also seeking to partner with researchers engaged in interventions, a key prerequisite for ultimately reaching practitioners.

These examples illustrate how the enhanced quality of research conducted by cross-disciplinary teams has resulted in positive decisions by funding agencies, notably NIH. Such increased support, as noted above, increases the likelihood that universities will respond to the incentives of resources and prestige, for example, by recognizing the value of such research through promotion and tenure decisions that celebrate rather than penalize collaboration and resulting, multiple-authored publications.

Complementing these cases, two chapters in the Kessel et al. volume reflect the experiences of a large multi-member team based in one center and reaching out to many others: Marmot[30] in the studies of aging and the social gradient in the UK, and Chesney and Coates[31] in their research on HIV/AIDS in San Francisco (and elsewhere).

Marmot's case[30] involves an extensive study of aging that is "both multidisciplinary and interdisciplinary . . . [It has] major content in economic, health–clinical, biological and health care and its determinants, social participation and cognitive psychology"[30] and involves scientists from several relevant disciplines. (Marmot himself is an epidemiologist.) The multidisciplinary aspect of the initial study entailed "each discipline working on its own area." But now Marmot reports "a flourishing interdisciplinary environment. For example . . . there's the usual debate as to whether health leads to socioeconomic position or socioeconomic circumstances lead to health. Collaboration between biological sciences and economists show that both are true."[30,e]

[e]Collaboration between epidemiologists and economists has yielded a comparison of the social gradient in health in English and American white men and women. Since one finding is that the Americans are less healthy than the British, Marmot's research has stimulated much media attention.[32,33]

Marmot reports that recognition of the significance of such findings **and** the interdisciplinary research process have enabled the center to become formalized as an Institute where members draw on other departments and disciplines in the UK and collaborate with biomedical and social scientists in Latin America, Africa, and Asia. Building on their policy work within the UK, Marmot's team has moved into the global health policy realm through involvement with WHO. Specifically, the Institute serves as host of the Commission on Social Determinants of Health: "The Commissioners, from every region of the world, have expertise in a number of areas apart from health. A major aim . . . is to convince governments and others that planning for health has to involve sectors other than 'health'; and to convince other sectors that [their] policies . . . have vital importance for health."[30]

Updating their chapter on HIV/AIDS prevention, Chesney and Coates[31] describe the changes in the Center for AIDS Prevention Studies (CAPS) since its founding in 1986.[f] They identify the organizational features that have kept the Center functioning productively:

> *Scientific innovation* depends on structure, process and people. The center grant provides the *structure* to stimulate new ideas and organize research projects into coherent programs addressing the full range of HIV/AIDS prevention policy issues. The Center has developed a process that encourages concepts to be developed into innovative research projects . . . and allows us to bring together the *people* . . . The Center is a place for sustenance of scholars devoting their careers to this effort and for the training of new scholars, domestically and internationally, so that the field can respond to future challenges.[31]

The Center for AIDS Prevention Studies now encompasses research across the spectrum of HIV/AIDS–related concerns, for example, oral acquisition of the virus by infants, medication adherence, and household coping mechanisms; HIV-prevention research in minority communities, involving scientists from universities in the U.S. and Puerto Rico; and policy and ethics. It also has strengthened ties to biomedical and clinical investigators at UCSF and to researchers in Africa, Asia, and Latin America. In addition, CAPS had received funding for training in prevention, dissemination of results, and translation of research into practice. Importantly in this context, Chesney and Coates[31] note approvingly the importance of the flexible mechanisms that NIH has now established with regard to the P30 mechanism.

[f]As the current director of CAPS, Stephen Morin contributed to the chapter Postscript.

Table 1. Factors facilitating and constraining transdisciplinary team science[4]

Factor	Facilitating	Constraining
Focus on major problems	PIs able to bring researchers together across disciplines and program-unifying themes	Some areas seen as unrealistic Lack of integrative research framework Few "how-to" models
Team members (PI et al.)	Possess complementary and intersecting skills Able to develop common language Positive open attitude Appreciative of others' knowledge Shared understanding of scientific problem Mutual trust and respect Open to mentoring others	See skills as competitive Tension between solo and collaborative work Power–prestige differences social and medical sciences Worry about diffusion of focus and loss of identity Research seen as time-consuming/multiple projects Disincentive for practitioners Sharing credit affects promotion, tenure, publications, funding
Training	Complementary training Mentored as grad students to participate in transdisciplinary research team SERCA grants for training in new field	Historical barriers across fields Location of departments Funding limited
Institutions	Support, promote, and fund centers, networks, and teams across disciplines, departments, and medical and social science faculties on same campus	Rigid university policies Centers lacking funds
Technology	Facilitate communication even when teams and researchers physically dispersed	
Funding	Foundations and government support network/team approach (e.g., MacArthur, NIH)	Grant applications more challenging, time-consuming
Publication		Journals discourage multiple authors Peer review hard to judge Need to frame more narrowly

PI, principal investigator; SERCA, Special Emphasis Research Career Award

In our view, the potential for CAPS to become truly transdisciplinary is embedded in all of its projects and successes, even though Chesney and Coates[31] write of themselves as doing "multidisciplinary research." More generally, in a manner similar to tobacco research, the fields of both HIV/AIDS and aging research appear to be promising foci for transdisciplinary attention. Because of their productivity and success, both domestically and internationally, Marmot's Institute and CAPS serve as prototypes that should promote new integrative thinking in these fields.

Issues and Implications from Review of Cases

Drawing on all the case studies in the Rosenfield and Kessel volume, we previously analyzed the factors and circumstances that facilitate and constrain innovation at the boundaries of the health and social sciences.[4,g] Reflecting on the primary theme of the NCI conference, viz., the evaluation of team science, we have revisited that analysis and sketched those factors that appear most salient for transdisciplinary team science in Table 1.

Several of the factors listed in Table 1 also emerged as central themes at the NCI conference. For example, the focus on a complex problem provides the unifying fulcrum for any successful team.[h] Given such a problem focus, team members can understand where their talents can be used and recognize the value of other competencies and perspectives. Further, to achieve such shared understanding, there is a need to establish a common, or at least mutually understood, language. We therefore suggest that along with establishing respect for the contributions of others, perhaps the first step toward building a transdisciplinary team is to develop a common understanding of the dimensions of an energizing problem, whether tobacco-related illnesses, HIV/AIDS, or cardiovascular diseases.

[g]In the course of that commentary, distinctions among multidisciplinary, interdisciplinary, and transdisciplinary research were presented.[4]

[h]"What might be called the-problematic-of-the-problem warrants further analysis since, in scientific practice, what constitutes 'the problem' is often the function or expression of a particular theoretical or disciplinary paradigm. How then do potential collaborators from different disciplines work their way toward a definition of 'the problem' that unites rather than divides them?"[4]

Two crucial elements for achieving such understanding relate closely to the training of team members and the institutional base for the project or program. Researchers who, as graduate students, medical students, or post-doctoral students, acquire understanding about the potential for transdisciplinary research will learn how to respect the value and values of others and to worry less about submerging their professional identity in the team process. And to provide a broad foundation for such a process, the institutional infrastructure of scientific research—universities, journals, and funders—all need to be aligned in support of transdisciplinary team science. Moreover, issues such as promotion, tenure, barriers between departments and faculties, authorship, peer review and grant applications can either support team science or constitute limiting factors. Such findings are reinforced by the 2005 National Academies report,[34] where the table of facilitating factors maps on to Table 1 here and to Rosenfield and Kessel's earlier analyses.[4]

In their overview of the NCI conference papers, Stokols et al. elaborate on these and other concerns, including the importance of evaluating the distinctive nature of the results of transdisciplinary team science where "the scientific, educational and translational aims of TS [team science] are highly diverse."[35] They also refer to the antecedents for successful collaboration, including team members' readiness. Nash,[36] in particular, provides important specificity on the necessary reorientation of training programs and supportive institutional settings, including ways to promote trust, shared competencies, and intellectual risk-taking.

Concern about sustained funding was a consistent theme at the 2006 NCI conference, as was the recognition that NIH support has made possible the innovative transdisciplinary team science reported there. Moreover, such endorsement remains vital for garnering financial and intellectual support from foundations and universities. With this in mind, it is worth highlighting several NIH funding mechanisms that have been noteworthy in facilitating sustained transdisciplinary innovation:

- The NIH Road Map prompts support across individuals and centers;
- P20 Mechanism for research consortia;
- R03 for graduate training;
- NIA support for inter-university teams, randomized control trials, and longitudinal studies; and
- overall NIH recognition and acceptance of multiple, team-based investigators drawn from the full range of medical, health, and social sciences.

What's Missing, What's Needed, What's Next?

Given these conclusions regarding increased recognition of the value of transdisciplinary science and its sustained funding, what's next? One issue raised by several contributors to the NCI conference is the challenge of forging a range of models and methods for team science.[35] More broadly, what ideas might help shape emerging and evolving team explorations of health across diverse disciplinary boundaries in the direction of authentic transdisciplinarity? Complementing the NCI conference papers, Higginbotham et al.[20] pointed to the salience of complexity theory and network theory, and the use of cyber-infrastructure. Similarly, the recent European Science Foundation Strategic Plan calls team science "synergy science" and encourages further exploration of the research process along with ways to reshape discipline structures.[9]

The multiplicity of disciplines, departments, institutions, investigators and sites implied by these views and inherent in the organization of transdisciplinary research as team science has led us to consider what kind of conceptual framework might help shape **and sustain** the evolving exploration of health across all these boundaries. Echoing Foster's decades-old concern,[3] the issue is whether, absent explicit efforts to establish certain characteristics of transdisciplinary team science and even with the best of innovative intentions, a familiar regressive pattern might emerge; that is, where researchers engage in projects involving multiple disciplines that are hierarchically structured. Is there an alternative to such hierarchical structuring?

In the original commentary on case studies of successful interdisciplinary collaboration, inspired by Cacioppo's writings and his research with Berntson,[37] we suggested that the concept of *heterarchy* provides an insightful frame for addressing "human and social problems that are patently complex, multidimensional, and interactive (over time and space)."[4] First introduced in 1945 by McCulloch, one of the pioneers in cognitive science,[38] the concept has been used by paleoanthropologists as they reconsidered the organization of human relations in early human society. Notable among them, Crumley[39] defined heterarchy as the "relation of elements to one another when they are unranked or when they possess the potential for being ranked in a number of different ways."[39] (See also von Goldammer et al.[40])

Several years later the notion of heterarchy is being explored in an increasing variety of areas.[i] Most relevant here, Crumley[48] presents heterarchy as a "robust social theory" because it explicates conditions for selection of an analytical framework that can address the following kinds of questions:

[i]These range from domains close to McCulloch's original scientific interests[41] to areas further afield such as evolution,[42] ecology,[43] and socio-political development,[44] and yet others that circle back to his passion for philosophy[45] and even poetry.[46] The single best sign of McCulloch's intellectual reach comes via the description of his collected papers at the American Philosophical Society.[47]

- How adequate is a model in relating the micro (individual) level to the macro (social) level?
- How adequate is a model in relating the conscious agency of social actors to the social structure in which they operate?
- Can a model provide an explanation for discontinuous and foundational changes in the system as a whole?

Such analyses have convinced us that viewing various facets of the scientific landscape through a heterarchical lens has significant power. In one direction, there are implications for how trans-boundary science is organized and institutionalized, with emphasis on "a network of elements [in this context, disciplines] sharing common goals in which each element shares the same 'horizontal' position of power and authority, each having an equal vote . . . Socially, a heterarchy distributes privilege and decision-making among participants . . . In an organizational context, [heterarchy's] beauty is the way in which it permits the legitimate valuation of multiple skills, types of knowledge or working styles without privileging one over the other."[j] In another, complementary direction, the research of Berntson and Cacioppo,[37] Ryff and Singer,[29] and others demonstrates that understanding the rich complexities of human life (e.g., health processes and outcomes) is most likely to emerge via work that embraces, in theory and research practice, integrative levels of analysis. Berntson and Cacioppo's principles of "multiple, non-additive, and reciprocal determinism" are important corollaries of integrative analysis.[37]

How, then, to conceive of the link between heterarchy and transdisciplinarity? Our propaedeutic proposition—*If transdisciplinarity is the approach for combining-cum-transcending disciplines in integrative, creative, "emergent" ways, heterarchy is both a heuristic metaphor and a potential analytic framework for operationalizing and managing such an approach.*

In less abstract terms, our earlier description of the CAPS foreshadowed a heterarchical frame of that transdisciplinary team. First, the Center's NIH center grant had made it possible to distribute resources for research and training over time and space. Second, changes in leadership have underlined that "rankings" of staff and discipline are constructively fluid. Third, as a central corollary, no discipline or perspective has permanent authorization over any others. As Chesney and Coates[31] point out, the Center has been the hub from which change has emanated—changes in leadership, investigators, research topics, and funding. The overarching focus has been on the process that leads to the most dynamic yet flexible operational style for examining the many levels and dimensions of HIV/AIDS prevention and control, from biomedical to public outreach, from the U.S. to many other countries. CAPS, in other words, is more than a network; it is a heterarchical arrangement of people and projects where processes supporting innovation are paramount.

Our extension of the concept of heterarchy moves it from analysis of complex social systems *per se* to the realm of organizational arrangements that can enhance the capacity to conduct and sustain team science around multi-level, multi-layered health issues located in dynamic social and cultural contexts. Drawing from the field of management science, where heterarchy is used as an analytical concept for research on corporate effectiveness,[50,51,k] and prompted by CAPS and other case studies in Kessel et al.,[27] we propose some initial guidelines for the understanding and assessment of team science capacity:

- establish degrees of flexibility in ranking of leaders, disciplines, and topics in the conduct, sequencing and re-sequencing of research activities[l];
- assess resilience in responding to changing conditions that require re-thinking basic premises (theoretical or methodologic), as well as effectiveness in communicating those changes to different constituencies; and
- assess team effectiveness in bridging multiple contexts within the same geographic site or across sites.

Finally, with such starting guidelines in mind, and given that NIH has developed a series of flexible funding mechanisms to facilitate complex research endeavors, we suggest that a creative next step in the process of conceptualizing and evaluating transdisciplinary team science would be to bring together scientists conducting boundary-crossing research and scholars engaged in elucidating the concept of heterarchy. One primary purpose of such a conversation would be to continue clarifying and sharpening the distinctions—in principle and practice—among multidisciplinary, interdisciplinary, and transdisciplinary research. More broadly, the goal would be to shape reflective substantive and organizational practices on the part of the next generation of transdisciplinary team scientists committed to examining the cultural and social systems in

[j]This quote comes from the *Wikipedia* entry for "heterarchy." Appropriately so, given another part of that entry–"A heterarchical structure processes more information more effectively than hierarchical design. An example of the potential effectiveness of heterarchy would be the rapid growth of the heterarchical Wikipedia project in comparison with the failed growth of the Nupedia project. Heterarchy increasingly trumps hierarchy as complexity and rate of change increase." See also Crumley (2007).[49]

[k]From 1999 to 2001 the Center for Organizational Innovation at Columbia University held a "Heterarchy Seminar". And von Goldammer et al.[40] have applied the concept of heterarchy to decision-making in multiple contexts.

[l]von Goldammer et al.[40] refer to this as "reverse osmosis" of the research process.

which biomedical health conditions are reciprocally and, indeed, heterarchically situated.[m]

Dan Stokols and his colleagues Kara Hall, Rick Moser, and Brandie Taylor exemplify the gold standard in cross-disciplinary collaboration. We greatly appreciate, and value, their generous and creative collegiality.

No financial disclosures were reported by the authors of this paper.

References

1. Paul BD, ed. Health, culture, and community: case studies of public reactions to health programs. New York: Russell Sage Foundation, 1955.
2. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
3. Foster GM. World Health Organization behavioral science research: problems and prospects. Soc Sci Med 1987;24:709–17.
4. Rosenfield PL, Kessel F. Fostering interdisciplinary innovation: the way forward. In: Kessel F, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science: case studies of interdisciplinary innovation. New York: Oxford University Press, 2003:378–413.
5. Judge A, Clark J. Development of trans-disciplinary conceptual aids. Union of International Associations, Brussels and Center for Interdisciplinary Creativity, Southern Connecticut State College. Available at: www.laetusinpraesens.org/docs/transveh.php.
6. Nicolescu B. The transdisciplinary evolution of the university condition for sustainable development. Available at: nicol.club.fr/ciret/bulletin/b12/b12c8.htm.
7. Nowotny H. The potential of transdisciplinarity. Available at: www.interdisciplines.org/interdisciplinarity/papers/5, n.d13.
8. Charter of Transdisciplinarity. First World Congress of Transdisciplinarity, Convento da Arrabida, Portugal, November 2–6, 1994, Article 14. Available at: nicol.club.fr/ciret/english/charten.htm.
9. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
10. Network for Transdisciplinarity in Science and Humanities. Projects 2003–2005. Available at: www.transdisciplinarity.ch/Projekte_e.html.
11. Network for Transdisciplinarity in Science and Humanities. About the transdisciplinarity-net. Available at: www.transdisciplinarity.ch/ueber_tdnet_e.html.
12. Polimeni J. Transdisciplinary research: moving forward. Int J Transdisciplinary Res 2006;1:1–3.
13. European Science Foundation. European Science Foundation Strategic Plan 2006–2010. Strasbourg: European Science Foundation. Available at: www.esf.org/fileadmin/be_user/publications/Plan20062010final.pdf.
14. Stokols DB. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
15. Kessel F, Rosenfield PL. Preface to new edition. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
16. Albrecht G. Philosophical thoughts on a transdisciplinary model of human health. In: Higginbotham N, Albecht G, eds. Transdisciplinary thinking in health social science research: definition, rationale and procedures. Newcastle: Centre for Clinical Epidemiology and Biostatistics, University of Newcastle, 1990.
17. Trostle J. Building research capacity for health social sciences in developing countries. Soc Sci Med 1992;35:1321–1420.
18. Albrecht G, Freeman S, Higginbotham N. Complexity and human health: the case for a transdisciplinary paradigm. Cult Med Psychiatry 1998;22:55–92.
19. Higginbotham N, Albrecht G, Connor L. Health social science: a transdisciplinary and complexity perspective. Melbourne: Oxford University Press, 2001.
20. Higginbotham N, Briceno-Leon R, Johnson N, eds. Applying health social science: best practice in the developing world. London: Zed Books, 2002.
21. Ramos-Jimenez P. Asia and the Pacific: Introduction. In: Higginbotham N, Albrecht G, Connor L. Health social science: a transdisciplinary and complexity perspective. Melbourne: Oxford University Press, 2001.
22. Erinosho L. Africa: Introduction. In: Higginbotham N, Albrecht G, Connor L. Health social science: a transdisciplinary and complexity perspective. Melbourne: Oxford University Press, 2001.
23. Briceno-Leon R. Latin America: Introduction. In: Higginbotham N, Albrecht G, Connor L. Health social science: a transdisciplinary and complexity perspective. Melbourne: Oxford University Press, 2001.
24. Hadiyono JEP. The development of a transdisciplinary approach to promote the rational use of drugs: the Indonesian experience. In: Higginbotham N, Briceno-Leon R, Johnson, N, eds. Applying health social science: best practice in the developing world. London: Zed Books, 2002.
25. Johnson NA, Higginbotham N, and Briceno-Leon R. Best practice and future innovation in applying social science to advancing the health of population. In: Higginbotham N, Briceno-Leon R, Johnson, N, eds. Applying health social science: best practice in the developing world. London: Zed Books, 2002.
26. Kessel F, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science: case studies of interdisciplinary innovation. New York: Oxford University Press, 2003.
27. Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
28. Olshansky SJ, Carnes BA. A journey through the interdisciplinary landscape of biodemography. Postscript 2006. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
29. Ryff CD, Singer B. Thriving in the face of challenge: the integrative science of human resilience. Postscript 2006. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
30. Marmot M. Social resources and health. Postscript 2006. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
31. Chesney MA, Coates TJ. The evolution of HIV prevention in San Francisco: a multi-disciplinary model. Postscript 2006. In: Kessel F, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science, 2nd ed. New York: Oxford University Press, 2008.
32. Cowell A. Study says older Americans less healthy than British. The New York Times. May 3, 2006.
33. Marmot M. The status syndrome: how social standing affects our health and longevity. New York: Henry Holt & Co., 2005.
34. Committee on Facilitating Interdisciplinary, National Academy of Sciences, national Academy of Engineering, IOM. Facilitating interdisciplinary research. Washington DC: The National Academies Press, 2005.
35. Stokols D, Hall KL, Taylor B, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
36. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.
37. Berntson GG, Cacioppo JT. A contemporary perspective on multilevel analyses and social neuroscience. In: Kessel F, Rosenfield PL, Anderson NB, eds. Expanding the boundaries of health and social science: case studies of interdisciplinary innovation. New York: Oxford University Press, 2003.
38. McCulloch W. A heterarchy of values determined by the topology of nervous nets. Bull Math Biophysics 1945:7:89–93.

[m]As we further explored writings on heterarchy, we discovered an extension of the idea in the field of international relations: *Panarchy*. Emerging as a meta-frame for networking networks, the concept could be relevant to the development of team science theory and practice. As Hartzog, one of the innovators in this area, states, "The emerging complexity of our social and political structures, composed of many interacting agents, combined with the increasing importance of network forms of organization, enabled by technologies that increase connectivity, propels the world toward a transformation that culminates in a global political environment that is made up of a diversity of spheres of governance, the whole of which is called panarchy. To clarify, global linkages between individuals and groups create transnational networks consisting of shared norms and goals."[52] Here we can only note that the Marmot case study[30] might demonstrate the implementation of a productive panarchic system in the sphere of health research.

39. Crumley CL. Heterarchy and the analysis of complex societies. In: Ehrenreich RM, Crumley CL, Levy JE, Heterarchy and the analysis of complex societies. Archeological Papers of the American Anthropological Association 1995;6:3.
40. von Goldammer E, Paul J, Newbury J. Heterarchy-hierarchy: two complementary categories of description. 2003. Available at: www.vordenker.de/heterarchy/het_intro_en.htm.
41. Arbib MA. Warren McCulloch's search for the logic of the nervous system. Perspect Biol Med 2000;43:193–216.
42. Combs AL. Daddy, why are people so complex? World Futures: J Gen Evolution 2006;62:464–72.
43. Andreas S. Heterarchy and ecology: maintaining and restoring balance in living systems. Presentation at the 2004 Institute for the Advanced Studies of Health Conference, San Francisco CA.
44. White JC. Incorporating heterarchy into theory on socio-political development: the case from Southeast Asia. Archeological Papers of the American Anthropological Association 1995;6:101–23.
45. von Foerster H. Metaphysics of an experimental epistemologist. 1995. Available at: www.vordenker.de/metaphysics/metaphysics.htm.
46. Kay LE. From logical neurons to poetic embodiments of mind: Warren S. McCulloch's project in neuroscience. Science in Context 2001;14:591–614.
47. American Philosophical Society. Warren S. McCulloch Papers. Available at: www.amphilsoc.org/library/mole/m/mcculloc.htm.
48. Crumley CL. Remember how to organize: heterarchy across disciplines. In: Beekman CS, Baden WW, eds. Nonlinear models for archeology and anthropology: continuing the revolution. Hampshire UK: Ashgate Publishing, 2005.
49. Crumley CL. Historical ecology: integrated thinking at multiple temporal and spatial scales. In: Hornborg A, Crumley CL, eds. The world system and the earth system: global socioenvironmental change and sustainability since the Neolithic. Walnut Creek CA: Left Coast Press, 2007.
50. Fairtlough G. The three ways of getting things done: hierarchy, heterarchy and responsible autonomy in organizations. Devon UK: Triarchy Press, 2005.
51. Wilken T. Heterarchy: the secret of Japan, Inc. Available at: futurepositive.synearth.net/2005/05/13.
52. Hartzog P. Panarchy: Governance in the network age. Available at: www.panarchy.com.

Of Mice and Mentors

Developing Cyber-Infrastructure to Support Transdisciplinary Scientific Collaboration

Bradford W. Hesse, PhD

Introduction

When Douglas Engelbart of the Stanford Research Institute (SRI) began refinements on an input device to simplify access to computing systems in 1962, he was setting into motion a cascade of events that would ultimately alter the ways in which scientists worked together. Colloquially, Engelbart referred to his prototype pointing device as a "mouse," a name he gave to the handheld unit when observing that the cord coming out of the back-end looked distinctively similar to a tail (the technical name for the patent was the X-Y Position Indicator for a Display System). Most computer users today recognize the mouse as a mainstay of graphical user computing: a way of pointing, clicking, and dragging "virtual" objects onto either a personal or shared workspace. What users do not recognize is that the invention came out of a radically new way of thinking about knowledge and science.

The Mouse That Roared

What Engelbart and his colleagues set out to do in 1962 was alter the social cognitive environment, or social ecology,[1,2] in which an "augmented"[3] science would take place. Unabashedly, the group had been influenced by the writings of Benjamin Lee Whorf,[4] who suggested that language as a human invention could influence the sophistication of thought: The better and more complete the system for symbolic representation, the better and more sophisticated the intellect it enabled.[4,5] Engelbart and his colleagues reasoned that electronic computer systems represented a natural extension of this thinking, as electronic systems were themselves frameworks for organizing symbolic representations. If the systems could be engineered correctly, they could be used to extend capacity in science. Recognizing that systems and science must co-evolve, the group introduced the term *bootstrapping*[6,7] (literally, to lift oneself up by the bootstraps) to convey a feeling for the iterative course this co-evolution must take.

The mouse was one of the first tools for thought[3] that the group bootstrapped into operation among a select group of scientists in what would come to be known as Silicon Valley.[5] Its purpose was to operate hand-in-hand with a system designed to portray computer data graphically on a screen, and thus give users access and control to a sophisticated set of underlying data patterns in ways that were enlightening and accessible. Using a mouse, the group reasoned, an architect could interact directly with a blueprint for an architectural design on the screen—a metaphor that was more comfortable and understandable than columns of architectural data arrayed in tables.[3] In the context of preventive medicine, an epidemiologist could interact directly with an interactively arrayed map of disease-registry data, looking for disease clusters or signals of outbreak.[8] Both of these ideas may seem commonplace today, but at the time the concept was quite revolutionary.

Another tool introduced by these early cyber-system pioneers was the concept of *hypertext*.[9] The concept was relatively simple. Most language is processed in a linear fashion, but new concepts are formed by making connections between linear strands of logical thought. The hypertext link was introduced as a mechanism for referring a reader to related information instantaneously at the click of the mouse. Although the use of hypertext gained only nominal popularity in personal computing systems, the real power of the mechanism became apparent once the global hypertext linking project, now known as the World Wide Web, matured. Soon, the basic functionality of hypertext was allowing scientists to build off each other's work in unprecedented ways, clicking from one document to the next in pursuit of a hyperlinked thread of continuous thought.

A third defining component of the framework was to enable better collaboration among scientists using online computer-supported cooperative work (CSCW) environments.[10,11] Also called *co-laboratories* (connoting a shared laboratory) or *collaboratories* (connoting a place for online collaboration), these online spaces supported researchers located in different parts of the country and in different time zones as they worked

From the Division of Cancer Control and Population Sciences, National Cancer Institute, Bethesda, Maryland

Address correspondence and reprint requests to: Bradford W. Hesse, PhD, National Cancer Institute, 6130 Executive Boulevard, MSC 7365, Bethesda MD 20892-7365. E-mail: hesseb@mail.nih.gov.

together in virtual space.[12–14] Indeed, completion of the human genome mapping project—one of the most ambitious examples of distributed team science in history—may have been made possible only by the collaborative information infrastructures put in place by biomedical informaticians.

Using Cyber-Infrastructure to Make Team Science Smarter

Early experiments in CSCW environments have had a mixed influence on scientific collaboration.[15,16] On the positive side, scientists who took early advantage of online systems published more prolifically, made more community contacts, and were more successful at requesting use of shared resources than those who were not online.[17] On the negative side, collaborative information environments were clearly not suited for all tasks. Virtual environments could never replace real-world social environments, synchrony, and propinquity in supporting the full gamut of collaborative activities.[13,15,18,19] Regardless of individual costs and benefits, new forms of work began proliferating[16] as individual scientists learned how to query the community as a whole and began coordinating the use of shared, but distant resources in both real and delayed time.[18]

In 2005, authors of a report by the Pew Charitable Trusts declared that online computing—the mouse, hypertext, and computer-supported collaboration—had made its way into the fabric of everyday life.[20] The Internet was no longer an experimental technology waiting for adoption; it was the "new normal." It had insinuated itself as an inseparable dimension of daily work life, and for many professionals it was altering the rules of engagement in substantive and life-altering ways. *New York Times* reporter Thomas Friedman quipped that many of the substantive changes brought about by diffusion of the Internet seemed to be happening "while we were all sleeping"; yet the changes are so monumental they are reshaping the ways in which wealth and power are distributed throughout the world.[21]

Normal science, as a collective enterprise, is experiencing the impact of the new normal firsthand. As Nobel Laureate and Cal Tech President David Baltimore declared when reflecting on changes within the biological community:

> Biology is today an information science. The output of the system, the mechanics of life, are encoded in a digital medium and read out by a series of reading heads. Biology is no longer solely the province of the small laboratory. Contributions come from many directions.[22]

In other words, the fabric of biological science has been permanently altered by the thinking enabled through augmentative information technologies. The life sciences, like many other sciences, are reorganizing themselves along multidisciplinary lines in order to grapple with this new perceived reality.

Grid Computing

One of the core developments in this new era of thinking is the concept of *grid computing*. In April 2005, the American Psychological Association ran a feature article in the *APA Monitor* quoting a University of Chicago professor who observed that the world appears to be quickly dividing into two camps: those who know about grid computing, and those who do not.[23] Those who know about grid computing understand that whole scientific communities have been working to assemble their data structures into an inter-operable lattice of mutually accessible collections of data, tools, and resources.[24] Users of this lattice, or grid, can share resources with each other in order to answer questions that are bigger than what any one single laboratory could solve. Consider how output from thousands of remote sensing devices can be brought together to give geophysicists an unfolding view of global climate change. Or consider how biomedical researchers can channel the terabytes of data collected around the human genome to unlock windows of opportunity for medical intervention. These large-scale, team-science tasks are enabled by the architectures underlying grid computing.[24–26]

Such is the rationale behind the National Cancer Institute (NCI)'s investment in caBIG (the **ca**ncer **B**iomedical **I**nformatics **G**rid).[25,27] Funded originally as an ambitious pilot project, the caBIG infrastructure project is working to provide scientists distributed throughout the NCI's Comprehensive Cancer Centers a common way of accumulating and analyzing data on intracellular processes; clinical manifestations; epidemiologic prevalence, mortality, and incidence; and treatment efficacy. The goal is to accelerate connections in knowledge needed to attack the multi-pronged challenge of cancer from the perspectives of prevention, early detection, diagnosis, treatment, and the long-term management of cancer as a chronic condition.[25,27] Ultimately, the purpose of the caBIG and other grid systems is to co-evolve new tools for thought to match the scope and complexity of science at the beginning of the 21st century. Some of the functionality encompassed by those tools is worth listing.

Transdisciplinary Discovery

New iterations of computer infrastructure, or cyber-infrastructure, are being funded by the National Science Foundation to support the high-performance computing needed to analyze complex, multidisciplinary relationships. The goal is to develop a new evolution of information infrastructure that will be "human-centered, world class, supportive of broadened participation in science and engineering, sustainable, and stable but extensible."[26] Once in place, the expanded resolution of these interconnected and multilevel data sets should open up a new era of discovery in which variables that have never been crossed before are juxtaposed in transdisciplinary analyses.[28] New and advanced data mining techniques are being introduced that can help accelerate the discovery of relationships based on applications of artificial intelligence and machine learning.[29] Understanding the relationship between genes and environment, overcoming health disparities, addressing the multiplex issues of cancer control and prevention are all areas of new discovery enabled by cyber-infrastructure.

Visualization

In the health sciences, efforts are underway to develop tools that can inform the gamut of transdisciplinary analyses from "cells to society."[30] At the cellular level, imaging software is being developed that will allow researchers to visualize macromolecular structures in 3-D, and to manipulate them in real time to reveal hidden aspects of the structure.[26] At the societal level, work is being done by the Open Geospatial Consortium (www.opengeospatial.org/) to develop standards for linking data sets with geographic descriptors. The resulting grid will allow GIS researchers to array anything from disease incidence measures to health knowledge measures geographically on a map.[24] The purpose will be to transform the ways in which health scientists, the public, and policymakers think about complex issues by using the power of cyber-infrastructure to make new graphic relationships accessible through powerful imaging techniques.[31]

Fusion

By some accounts, discussions in the 1970s were focused on the anticipation that there would simply not be enough data to fulfill the promise of advanced computing capabilities. Today, some say, we are "surveying ourselves to death;" that we have more data than we know how to handle and as a result we spend very little of our time integrating findings across data sources.[28] At the very least, this means that we are missing lost opportunities for discovery and decision making. More disconcertedly, we are wasting millions of scarce research dollars on data that are never connected, that never contribute jointly to solving a new but common analytic problem, and that simply stagnate or go unused. Cyber-infrastructure allows for the fusion of related, but heretofore disconnected, data sources.

Decision Support

In previous generations of scientific research, decisions about design and methodology were usually left up to individual researchers operating within isolated laboratories and dependent on the glacial pace of print-text publishing for information from the field. With the advent of the first generation of online collaboratories, scientists began making decisions about the future directions of their research based on the tacit knowledge of scientific colleagues shared online.[12,14] Digital libraries now make it possible to scan the full history of some disciplines with a few simple search terms. Evolution of the digital object identifier (DOI) made it possible for scientists to cross literatures online, jumping through a hyperlink to an online version of an article from the cited reference of another.[32] The development of Web 2.0 technologies (i.e., social computing) is driving this trend further by opening up an online "commons" of scientific knowledge built by volunteers from all stripes and areas of research, the most well known experiment of this type being the online knowledge repository Wikipedia.[33] Similarly, Google Scholar™ is an example of an online search engine that was designed to cross disciplinary silos in retrieving publications.

Policymaking

Changing public policy is often difficult. It requires a honed, persuasive argument relying on credible evidence to persuade and instruct.[34] Once a year, organizers of the Technology, Entertainment, and Design (TED) conference in Monterrey, California invite world-renowned speakers to give "the talk of their lives" (videos are archived and made available to the public at www.TED.com). In February 2006, organizers invited global health expert Hans Rosling to speak at the conference. Using data he had assembled from public health institutions around the world, Rosling gave an engaging presentation that served to shatter audience myths about the nature of poverty, health, and mortality in the Third World. Those data are already driving discussions among policymakers within the European Union, and are generating discussions in policy circles around the globe and illustrate how data synthesis can play an important role in policy change and policymaking. Using the power of connected data sources, scientists can make more compelling arguments to policymakers.

Using Team Science to Make Cyber-Infrastructure More Useful

The promise of grid computing is nothing more than audacious. To create an infrastructure for sharing resources openly in an unfettered information environment across disciplines requires a significant change in culture and incentives. Many less ambitious projects have failed precisely because they did not take into account the incentives and social structures needed to support successful collaboration.[5,11,15] In short, these projects failed, not because of technologic problems, but because network designers failed to heed the lessons learned from team science. In contrast, many examples of success with technologically inferior systems exist precisely because team members were willing to think creatively in devising workarounds for the shortcomings of the technology.[35,36] These projects were successful because of the power of creative collaboration.

The story of cyber-infrastructure, then, lies as much in the study of team science—in collaboration readiness—as it does in the study of new technology—in technology readiness.[13] In this way, the discussions encapsulated in this special issue are especially relevant to the task of building a world-class computer infrastructure for advancing scientific goals. The discussion of evaluation, for example, is directly pertinent to the system designer's ongoing goal of optimizing output. As the science of transdisciplinary evaluation evolves,[37] robust but informative evaluation strategies can be put in place to ensure that the social and technical subsystems[38] of an online science environment work together to meet intended project goals.[15,35]

Likewise, if the benefits from massive data structures interconnected through grid architectures are to materialize, they will come about because of the readiness and willingness of the scientific community to behave in transdisciplinary ways.[37] Research funding agencies and academic policymakers can nurture that process by offering incentives to change the context in which scientific collaboration occurs.[2] Collaborative leaders[39] in preventive medicine can, and should, emerge to help structure the foundations for mass collaboration[33] needed to solve problems of unprecedented complexity in an increasingly connected global environment.

Most importantly, mentors are needed who can take the challenge of modeling new behaviors at a time when the norms of scientific productivity and quality are uncertain. The task will be to move forward with eyes wide open, restructuring their teaching efforts to take full advantage of investments in team science and cyber-infrastructure, while clinging tenaciously to the principles of quality and evidence that must inherently govern scientific collaboration.

No financial disclosures were reported by the author of this paper.

References

1. Montero M, Stokols D. Psychology and the Internet: a social ecological analysis. CyberPsychology & Behavior 2003;6:59–72.
2. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
3. Engelbart DC. Augmenting human intellect: a conceptual framework. Summary Report. Palo Alto CA: Stanford Research Institute, October, 1962.
4. Adams P. Language in thinking: selected readings. Harmondsworth: Penguin, 1972.
5. Bardini T, Friedwald M. Chronicle of the death of a laboratory: Douglas Engelbart and the failure of the knowledge workshop. History of Technology 2002;23:193–212.
6. Engelbart DC. Augment, bootstrap communities, the Web: what next? In: CHI 98 conference summary on human factors in computing systems. Los Angeles, California, United States: ACM Press, 1998.
7. Engelbart DC, Jeff R. Bootstrapping our collective intelligence. ACM Comput Surv 1999;31(4es):38.
8. Ellisman M, Brady M, Hart D, Lin F-P, Miller M, Smarr L. The emerging role of biogrids. Commun ACM 2004;47:52–7.
9. Nelson TH. Complex information processing: a file structure for the complex, the changing and the indeterminate. In: Proceedings of the 1965 20th national conference. Cleveland OH, United States: ACM Press, 1965.
10. Almes G, Cummings J, Birnholtz JP, Foster I, Hey T, Spencer B. CSCW and cyberinfrastructure: opportunities and challenges. In: Proceedings of the 2004 ACM conference on computer supported cooperative work. Chicago IL: ACM Press, 2004.
11. Collins RW. CSCW: an opportunity for action research. In: Proceedings of conference on organizational computing systems. Milpitas, California, United States: ACM Press, 1995.
12. Finholt T. Collaboratories as a new form of scientific organization. Econ Innov New Techn 2003;12:5–25.
13. Olson G, Teasley S, Bietz M, Cogburn D. Collaboratories to support distributed science: the example of international HIV/AIDS research. Proceedings of the SAICSIT 2002:44–51.
14. Finholt T, Olson G. From laboratories to collaboratories: a new organizational form for scientific collaboration. Psychological Science 1997;8:28–35.
15. Sonnenwald DH. Scientific collaboration: a synthesis of challenges and strategies. In: Cronin B, ed. Annual Review of Information Science and Technology. Medford NJ: Information Today, 2007.
16. Sproull L, Kiesler S. Connections: new ways of working in the networked organization. Cambridge MA: MIT Press, 1991.
17. Hesse BW, Sproull L, Kiesler SB, Walsh JP. Returns to science: computer networks in oceanography. Commun ACM 1993;36:90–101.
18. Hesse BW, Werner CM, Altman I. Temporal aspects of computer-mediated communication. Computers in Human Behavior 1988;4:147–65.
19. Olson G, Olson J. Distance matters. Human-Computer Interaction 2000;15:139–78.
20. Pew Foundation. Trends 2005: Information for the Public Interest. Washington DC: Pew Research Center, 2005.
21. Friedman TL. The world is flat: a brief history of the twenty-first century. 1st updated and expanded ed. New York: Farrar, Straus and Giroux, 2006.
22. Denning PJ. Computing is a natural science. Commun. ACM 2007;50:13–8.
23. Greer M. Infrastructure for the science of psychology. Monitor on Psychology 2004:62.
24. Abbas A. Grid computing: a practical guide to technology and applications. Hingham MA: Charles River Media, 2004.
25. Buetow KH. Cyberinfrastructure: empowering a "third way" in biomedical research. Science 2005;308:821–4.
26. National Science Foundation. Cyberinfrastructure Vision for 21st Century Discovery. Arlington VA: National Science Foundation, March 2007.
27. Hesse BW. Harnessing the power of an intelligent health environment in cancer control. Stud Health Technol Inform 2005;118:159–76.
28. Agresti WW. Discovery Informatics. Communications of the ACM 2003;46:25–8.
29. Moore JH. Bioinformatics. J Cell Physiol 2007;213:365–9.
30. Abrams DB. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav 2006;33:515–31.
31. Bederson B, Shneiderman B. The craft of information visualization: readings and reflections. Amsterdam; Boston: Morgan Kaufmann, 2003.
32. Grudin J. Crossing the divide. ACM Trans Comput-Hum Interact 2004;11:1–25.
33. Tapscott D, Williams AD. Wikinomics: how mass collaboration changes everything. New York: Portfolio, 2006.

34. Nelson DE, Brownson RC, Remington PL, Parvanta C, eds. Communicating public health information effectively: a guide for practitioners. Washington DC: American Public Health Association, 2002.
35. Sonnenwald DH, Whitton MC, Maglaughlin KL. Evaluating a scientific collaboratory: results of a controlled experiment. ACM Trans Comput-Hum Interact 2003;10:150–76.
36. Toffler A, Toffler H. War and anti-war: survival at the dawn of the 21st century. 1st ed. Boston: Little, Brown, 1993.
37. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
38. Pava CH. Managing new office technology: an organizational strategy. New York, NY: Free Press, Collier Macmillan, 1983.
39. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.

Toward Cross-Sectoral Team Science

Bern Shen, MD, MPhil

Introduction

The papers in this supplement to the *American Journal of Preventive Medicine*[1–15] reflect the growing awareness that in an age of open-source innovation and collaboration, it has become increasingly urgent to understand when and how to foster and enhance transdisciplinary research in fields including prevention and public health. Collaborative approaches make sense in these fields because many of the problems are complex, require action across traditional boundaries or communities of interest, and are susceptible to "tragedy of the commons"[16] and "free rider" issues. *Heterosis*, better known in high school biology as hybrid vigor, can arguably apply equally to public health and research programs as to strains of corn, and combining the best from several approaches may well help to transform current research structures and incentives to better enable so-called *team science* to fulfill its promise.

The NIH and National Academies, among other groups, increasingly have recognized the usefulness of interdisciplinary and collaborative approaches to complex problems.[17] To be sure, these have potential downsides or limitations; for example, Yale psychologist Irving Janis's concept of "groupthink,"[18] Fred Brooks' point in *The Mythical Man-Month*[19] that increasing the size of a project team can perversely incur crippling inefficiencies and coordination costs; or the difficulties in the training, promotion, and retention of scholars who don't fit neatly within existing departmental boundaries.[20] For the most part, however, two heads are better than one, the wisdom of crowds[21] trumps that of most individuals, and tackling complex research questions from multiple angles confers advantage.

Thus, while many academic research groups, for-profit companies, and even philanthropies still largely operate in an insular, competitive mode, a few notable exceptions are exploring—and finding success in—alternative models. Examples of these collaborative, cross-sectoral efforts in biomedical science include various recipients of the NIH "P" series grants; the SNP (single nucleotide polymorphism) Consortium and HapMap Project; the BioBricks Foundation; the Public Library of Science; and similar initiatives in Canada[22] and the European Union.[23] Others with more of a public health flavor include the NIH exploratory centers for interdisciplinary research[24] and its program on public–private partnerships,[25] the Grand Challenges for Global Health initiative,[26] and the WHO-sponsored Medicines for Malaria Venture.[27] Well-known examples in industry include InnoCentive,[28] which posts problems from "seekers" and awards bounties to "solvers"; and P&G's Connect + Develop program,[29] which fosters external sources of product ideas.

Of course, the term *collaborative research* is a broad rubric, and this article will not discuss, for example, efforts such as Folding@home or FightAIDS@home, which use spare computing power donated by thousands of individuals around the world to enable powerful computing platforms for molecular modeling and drug discovery.[30] Rather, we will focus on three conceptual dimensions reflected in the rapidly expanding literature on research collaborations:

Team: collaborations across laboratories or institutions;

Approach: collaborations across disciplines, whether the approach is multidisciplinary, interdisciplinary, or transdisciplinary; and

Goal: collaboration across translational stage, that is, the spectrum from basic research through applied research or development, to sustainable implementation or commercialization.

These **TAG** dimensions are illustrated in Figure 1, and are elaborated below.

In Figure 1, three dimensions of collaboration define a space in which we can locate various types of research efforts. Point A represents a minimally collaborative, somewhat traditional model of basic research within a single discipline, and laboratory or institution. In contrast, Point B denotes a multi-institutional research collaboration within a single discipline, as often occurs among professional colleagues who happen to be located in different labs or universities. Similarly, Point C indicates a multidisciplinary/interdisciplinary collaboration within a single institution, for example, experts in public health, law, and behavioral science working together to study issues around tobacco advertising.

While the above points are located in the "back plane" of the diagram, representing predominantly academic research with little intention to translate into large-scale, sustainable implementations or commercialization, other points "in front" of this back plane

From the Digital Health Group, Intel, and the Department of Clinical Pharmacy, University of California San Francisco, San Francisco, California

Address correspondence and reprint requests to: Bern Shen, MD, MPhil, UCSF Department of Clinical Pharmacy, Box 0613, 521 Parnassus Avenue, San Francisco CA 94143. E-mail: bernshen@gmail.com.

0749-3797/08/$–see front matter

doi:10.1016/j.amepre.2008.05.013

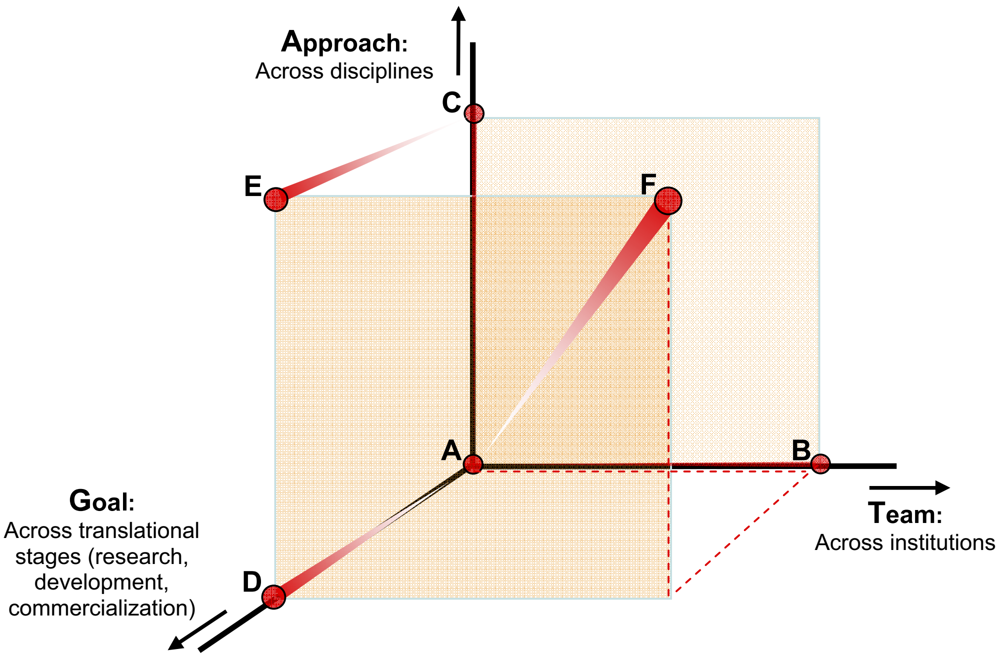


Figure 1. Dimensions of collaboration

represent efforts along the spectrum of translation, from basic research through applied research, to the development and scaling up of actual products or solutions. Point D, for example, could represent a project in a traditional industrial central research lab or a clinical process–improvement group, in which the work occurs more or less within a single discipline and within a single institution, but aims to build from basic or applied research to create a real-world intervention or solution. Point E, on the other hand, might describe a traditional commercial product–development effort, in which several disciplines (e.g., ethnography, design, engineering, legal/regulatory, marketing, and sales) are brought to bear on getting a product onto the market. Finally, Point F would represent a multi-institutional, multidisciplinary/interdisciplinary collaboration across translational stages, as the two dozen NIH-sponsored Clinical and Translational Science Awards (CTSA)[31] centers or numerous small business innovation research (SBIR) grant recipients are beginning to exemplify.

Since the inherent nature of prevention and public health tends to produce pragmatic, implementable solutions linked to measurable improvements in population outcomes, research in those fields tends to move off of the back plane of Figure 1, in contrast to academic disciplines in which, as Chesbrough observes, "unsurprisingly, when an organization rewards the quantity of patents or papers produced, the R&D organization responds by generating a large number of patents or papers, with little regard as to their eventual business relevance."[32] Additional impediments to establishing cross-sectoral collaborations among universities, government funding agencies, private corporations, foundations, and nongovernmental organizations are described in the proceedings of the 2007 National Cancer Institute Conference on the Future of Consumer Health Information Technologies.[33]

What are some specific strategies for encouraging and implementing collaborative research? In the academic sphere, a 2004 survey by the National Academies suggested that interdisciplinary research could best be promoted by fostering a collaborative environment, providing faculty incentives (including hiring and tenure policies), and providing seed money for interdisciplinary pilots.[34] In the for-profit sphere, companies have collaborated with universities over the years, supporting path-finding research through grants, donations in kind, bidirectional internships or sabbaticals, and even setting up "lablets" on or adjacent to university campuses.[32] Intel's Digital Health group has built on this history and has implemented a "research commons" model along with a number of universities. The reasoning is that one way to accelerate progress in an emerging field is to reduce unnecessary redundancy. Under this arrangement, research groups at different universities each chip in and cross-license tools and technology; original inventors retain rights over their intellectual property, but in the meantime, investigators don't have to spend (for example) the first 3 years of a 4-year grant re-inventing technology that already exists at another university before getting to the outcome studies that are the actual point of interest.

In addition to academia, industry, and government, at least two other categories of new entrants and partners are entering the research ecosystem. One category includes consumers or patients themselves, who can contribute to Web 2.0 initiatives[35] such as "crowdsourcing," user-generated content, and self-organization into patient advocacy and support groups. The other, partially overlapping, category of new research partners is private philanthropy. With an estimated \$300 billion in philanthropic contributions in the U.S. in 2006, of which roughly 17% were to medical institutions,[36] even if only a fraction of this flows to research, philanthropies represent a source of funding not far behind the \$28 billion annual NIH budget.[37] Donor-sponsored research, while not uncontroversial, has injected new funds and energy into particular disease areas and can complement federal research funding to help focus on public health issues, support transdisciplinary research, fund infrastructure and overhead, and encourage new organizational structures.[38,39]

Looking ahead, it seems likely that the blurring of institutional, disciplinary, and translational boundaries by various TAG teams comprising diverse combinations of researchers, industry partners, patients, and philanthropies will spawn new research arrangements, accelerate discovery, and ultimately improve population health outcomes. The papers in this supplement mark some of the early milestones in that evolution.

No financial disclosures were reported by the author of this paper.

References

1. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
2. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
3. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
4. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
5. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.
6. Hiatt RA, Breen N. The social determinants of cancer: a challenge for transdisciplinary science. Am J Prev Med 2008;35(2S):S141–S150.
7. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008;35(2S):S151–S160.
8. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
9. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
10. Holmes JH, Lehman A, Hade E, et al. Challenges for multilevel health disparities research in a transdisciplinary environment. Am J Prev Med 2008;35(2S):S182–S192.
11. Leischow SJ, Best A, Trochim WM, et al. Systems thinking to improve the public's health. Am J Prev Med 2008;35(2S):S196–S203.
12. Emmons KM, Viswanath K, Colditz GA. The role of transdisciplinary collaboration in translating and disseminating health research: lessons learned and exemplars of success. Am J Prev Med 2008;35(2S):S204–S210.
13. Mabry PL, Olster DH, Morgan GD, Abrams D. Interdisciplinary and systems science to improve population health: a view from the NIH Office of Behavioral and Social Science Research. Am J Prev Med 2008; 35(2S):S211–S224.
14. Kessel FS, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. Am J Prev Med 2008;35(2S):S225–S234.
15. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med 2008;35(2S):S243–S249.
16. Hardin G. The tragedy of the commons. Science 1968;162:1243– 48.
17. Hernandez LM, DG Blazer, eds. Genes, behavior, and the social environment: moving beyond the nature/nurture debate. National Academies Press, 2006.
18. Janis I. Groupthink: psychological studies of policy decisions and fiascoes. 2nd ed. Boston MA: Houghton Mifflin, 1982.
19. Brooks FP. The Mythical Man-Month: essays on software engineering. 2nd ed. Addison-Wesley, 1995.
20. Carey GE, Smith JA. Jack-of-all-trades, master of none: postgraduate perspectives on interdisciplinary health research in Australia. BMC Health Serv Res 2007;7:48. doi: 10.1186/1472-6963-7-48.
21. J Surowiecki. The Wisdom of Crowds. Anchor Press, 2005.
22. Hall JG, Bainbridge L, Buchan A, Cribb A, et al. A meeting of minds: interdisciplinary research in the health sciences in Canada. CMAJ 2006; 175:763–71.
23. Available at: ec.europa.eu/research/fp7/understanding/fp7inbrief/structure_en.html.
24. Available at: nihroadmap.nih.gov/interdisciplinary/exploratorycenters/.
25. Available at: nihroadmap.nih.gov/publicprivate/.
26. Available at: ppp.od.nih.gov/pppinfo/examples.asp.
27. Available at: www.cdc.gov/ncidod/eid/vol7no3_supp/bond.htm.
28. Available at: www.innocentive.com/.
29. Available at: secure3.verticali.net/pg-connection-portal/ctx/noauth/PortalHome.do.
30. Tapscott D, Williams AD. Wikinomics: how mass collaboration changes everything. Portfolio Press, 2006.
31. NationalCenterforResearchResources. Clinical and translational science awards to transform clinical research. Available at: www.ncrr.nih.gov/ncrrprog/roadmap/CTSA_9-2006.asp.
32. Chesbrough H. Open business models: how to thrive in the new innovation landscape. Harvard Business School Press, 2006.
33. Bosworth A, Shen B, Crounse W. National Cancer Institute Conference on the future: consumer health information technologies. The future: consumer health information technologies 2007; http://videocast.nih.gov/summary.asp?live=6327.
34. Committee on Science, Engineering, and Public Policy. Facilitating interdisciplinary research. National Academy Press, 2004.
35. Available at: www.mckinseyquarterly.com/How_businesses_are_using_Web_20_A_McKinsey_Global_Survey_1913.
36. NY Times editorial. Charity begins in Washington. 22 Jan 2008.
37. Available at: www.nih.gov/about/budget.htm.
38. Phillips K. The application of business models to medical research: interviews with two founders of directed-philanthropy foundations. Health Aff 2007;26:1181–5.
39. Gruman J, Prager D. Health research philanthropy in a time of plenty: a strategic agenda. Health Aff 2002;21:265–9. Available at: content.healthaffairs.org/cgi/reprint/21/5/265.

Moving the Science of Team Science Forward

Collaboration and Creativity

Kara L. Hall, PhD, Annie X. Feng, EdD, Richard P. Moser, PhD, Daniel Stokols, PhD, Brandie K. Taylor, MA

Abstract: Teams of scientists representing diverse disciplines are often brought together for purposes of better understanding and, ultimately, resolving urgent public health and environmental problems. Likewise, the emerging field of the science of team science draws on diverse disciplinary perspectives to better understand and enhance the processes and outcomes of scientific collaboration. In this supplement to the *American Journal of Preventive Medicine*, leading scholars in the nascent field of team science have come together with a common goal of advancing the field with new models, methods, and measures. This summary article highlights key themes reflected in the supplement and identifies several promising directions for future research organized around the following broad challenges: (1) operationalizing cross-disciplinary team science and training more clearly; (2) conceptualizing the multiple dimensions of readiness for team science; (3) ensuring the sustainability of transdisciplinary team science; (4) developing more effective models and strategies for training transdisciplinary scientists; (5) creating and validating improved models, methods, and measures for evaluating team science; and (6) fostering transdisciplinary cross-sector partnerships. A call to action is made to leaders from the research, funding, and practice sectors to embrace strategies of creativity and innovation in a collective effort to move the field forward, which may not only advance the science of team science but, ultimately, public health science and practice.
(Am J Prev Med 2008;35(2S):S243–S249) © 2008 American Journal of Preventive Medicine

Introduction

The emerging field of the science of team science draws together diverse disciplines to better understand and inform the collaborative processes and outcomes of team science. Team science can be conducted within a single, focused discipline, or can span different disciplines. The degree of variation across disciplines, as well as the breadth of levels of analysis (from cells to society), can affect the size and complexity of a given team. As such, the degree of complexity of a given problem that a team tackles can, in turn, influence the breadth and degree of the integration of disciplinary knowledge needed to explain or solve that problem. In the authors' view, the nascent field of the science of team science is currently in a descriptive or taxonomic phase of its development, during which key terms are being debated and defined as well as operationalized in specific contexts, and are being integrated into broader conceptual frameworks.[1,2] This supplement to the *American Journal of Preventive Medicine* seeks to consolidate recent work in this field by assessing a variety of conceptual issues that must be addressed as a basis for informing future team science initiatives—for instance, examining ways to categorize and measure collaborative efforts; developing models to conceptualize key aspects of the field; and devising strategies to enhance, support, and sustain team science projects.

During both the 2006 conference[3] and the development of this supplement, a variety of themes emerged that revealed knowledge gaps in the field and stimulated ideas and dialogues to guide future research. These themes pertain to: (1) the challenges associated with distinguishing between and empirically operationalizing unidisciplinary and cross-disciplinary approaches to team science and training; (2) the efforts to integrate alternative conceptualizations of multilevel readiness for team science; (3) the development of strategies for ensuring the sustainability of transdisciplinary team science; (4) the need to create new models and practical strategies for training transdisciplinary scientists; (5) the development of new models, methods, and measures for evaluating the processes and outcomes of team science; and (6) the forging of new transdisciplinary partnerships among universities, governmental agencies, nongovernmental organizations (NGOs), private foundations, and corporations.

From the Division of Cancer Control and Population Sciences, National Cancer Institute (Hall, Feng, Moser), the Office of Portfolio Analysis and Strategic Initiatives, NIH (Taylor), Bethesda, Maryland and the School of Social Ecology, University of California Irvine (Stokols), Irvine, California

Address correspondence and reprint requests to: Kara L. Hall, PhD, Division of Cancer Control and Population Sciences, National Cancer Institute, 6130 Executive Boulevard, Room 4080, Bethesda MD 20850. E-mail: hallka@mail.nih.gov.

doi:10.1016/j.amepre.2008.05.007

Toward an Integrative Taxonomy of Team Science

A central focus, to date, in the taxonomy of team science relates to the number of disciplines involved in a team and the kinds of interactions that occur across different disciplines. As is evident from a number of the articles included in this supplement,[1,2,4] the predominant conceptualization thus far has been Rosenfield's[5] definitions of and distinctions among unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary collaborations.

Although this supplement's primary focus is on transdisciplinary team science, there is not yet an agreed-upon definition of **transdisciplinarity**. In addition to the discrepancies among different definitions of transdisciplinarity, there is also considerable debate about whether or not distinct differences exist between interdisciplinarity and transdisciplinarity. In funding, in practice, in research, and in scholarly writing, the terms **interdisciplinary** and **transdisciplinary** have been used interchangeably, referencing both similar and different connotations in various settings. Some scholars suggest that there are no differences among multidisciplinary, interdisciplinary, and transdisciplinary approaches to research.[6] The plurality of definitions and operationalizations of these concepts are embedded within the different perspectives and circumstances in which collaborative sciences are conducted. For instance, Rosenfield's definitions[5] of interdisciplinary and transdisciplinary science describe research collaborations in which the intended scientific outcomes focus on a common problem (e.g., obesity), whereas the NIH Roadmap for Medical Research[6,7] describes interdisciplinary research more broadly as involving the creation of hybrid disciplines (e.g., biochemistry, psychoneuroimmunology). Furthermore, greater clarity is needed with regard to the dimensions underlying the concept of *scientific discipline* (typically defined in terms of its substantive concerns, methodologic approaches, and level of analysis) to help further elucidate what is meant by unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary science. Another facet of team science pertains to the definition and implementation of transdisciplinary *action research*, which involves collaborations among scientists and practitioners.[8] For example, in the field of social work, the term *interprofessionalism* has been used to describe cross-disciplinary endeavors that bridge the work of researchers with practitioners.[9]

Such variations in definitions and operationalizations of key terms can result in highly divergent measurement approaches to evaluating team science, which are likely to perpetuate confusion in the literature and impede progress in the science of team science.[1] In order to build a field with a strong science base that can be synthesized and generalized, greater clarity in basic terminology is essential for establishing a strong foundation for future studies. To better understand and evaluate the value-added qualities of transdisciplinary science, it is important that researchers in this area work together to cultivate common ground as they establish shared theoretical frameworks and measurement strategies that can be used to guide future team science endeavors.

Some of the articles in this supplement suggest that the distinctions between interdisciplinary and transdisciplinary research become more pronounced when viewed from the alternative vantage points of basic biomedical versus behavioral sciences.[10,11] To date, much of the conceptualization and investigation around interdisciplinary and transdisciplinary collaboration processes and outcomes has been led by behavioral scientists, and, as such, many of the evaluation strategies use behavioral methodologies (e.g., self-report surveys, latent variable analyses). It is clear that the study of cross-disciplinary team science (i.e., the science of team science) must bring together diverse perspectives from all levels of analysis to foster the development of a full spectrum of conceptual, theoretical, and methodologic innovations spanning multiple disciplinary boundaries. This can occur, for example, by utilizing qualitative methods to learn more about the different goals and motivations that prompt cross-disciplinary collaborations (e.g., collaborations based on the sharing of expensive laboratory equipment or specimen analyses versus those organized around the integration of intellectual ideas and frameworks spanning two or more fields); these findings can be used to develop rich conceptual and theoretical models and then can be tested in subsequent studies examining team science collaborations.

Much of the work discussed in this supplement revolves around large cross-disciplinary research initiatives.[12–14] This emphasis on large-scale, cross-disciplinary initiatives neglects several important questions. For instance, what kinds of team science programs have been pursued outside of this context? What is known about unidisciplinary team science? How does unidisciplinary team science compare to other types of cross-disciplinary team science collaborations (e.g., multidisciplinary, interdisciplinary, or transdisciplinary research) in its efforts to effectively and efficiently solve complex health problems? What basic principles are transferable to cross-disciplinary science? What are the challenges that distinguish unidisciplinary team science from cross-disciplinary team science? What can be learned from smaller-scale, cross-disciplinary—and more specifically, transdisciplinary—initiatives?[15] For instance, could smaller team science endeavors have fewer infrastructure constraints or less "drag" and, hence, greater flexibility and sustainability—resulting in increased creativity and efficiency?[16,17] Furthermore, can terms be developed that capture all types of cross-disciplinary team science (including multidisciplinary, interdisciplinary, and transdisciplinary sole-investigator, as well as collaborative, projects)? Is there a need to have different terms for team science that incorporate areas outside of academia, such as community-based participatory research or dissemination and implementation science?[8,18,a]

Team Science Readiness from a Social–Ecologic Perspective

Another important theme reflected in several articles in this supplement is the conceptualization and measurement of readiness for collaboration. This facet of team science has been conceptualized and measured in a variety of ways—for instance, in terms of individual and group research orientations, organizational and technologic resources that enhance the capacity for collaboration,[4,12,17] and the scientific readiness of different fields for collaborative integration.[11,21]

Stokols et al.[17] identified collaboration-readiness factors nested within a social–ecologic framework, including factors such as shifts in individuals' research orientations and their attitudes toward collaboration[12]; the availability of specific communication tools and cyber-infrastructural resources[22]; and funding agencies' willingness to invest in center-based, multiple-principal investigator grants.[10] In an increasingly globalized world, the demands for cross-national collaborations in health science, engineering, and technology will continue to grow. Also, as funding streams diminish, the need to coordinate and integrate health research efforts among academic institutions, government agencies, private corporations, and foundations will become increasingly important.[8,18,21,23] How can these sectors be brought together effectively and work toward the common goal of improving human health? What are the specific collaborative challenges inherent in collaborations that span multiple sectors?

Klein[1] in this supplement discussed the international scope of research on team science. The identification and implementation of the most effective strategies for enhancing global collaboration in the expanding domain of team science have yet to be further explored. Ensuring the success of transdisciplinary team science in the global arena requires an understanding of and sensitivity to cultural differences and their impact on teamwork.

The authors propose that future research explicitly consider multiple levels and dimensions of readiness for transdisciplinary team science, nesting certain levels within others and conducting in-depth case studies to identify which types of readiness factors (e.g., psychological, interpersonal, organizational, societal, technologic, scientific) exert the greatest influence on the effectiveness of team science projects and initiatives. A readiness framework can help generate appropriate multilevel interventions to increase the success of transdisciplinary team science. For instance, at the interpersonal level, understanding a team's readiness to engage in group processes to create common ground, common language, and shared goals can lead to the development of workshop modules to foster improved communications skills and team cohesiveness.[17] To date, evaluations of transdisciplinary initiatives have not given much attention to the relative impact of these diverse readiness factors on the effectiveness of team science, nor have they identified either the role that these readiness factors might have played in the successful implementation of an initiative or the ways in which multiple readiness factors jointly affect the processes and outcomes associated with transdisciplinary team science initiatives.

The Sustainability of Transdisciplinary Team Science

Critics of transdisciplinary team science, in addition to being concerned about the volume of funds directed toward transdisciplinary team science and away from unidisciplinary research, contend that once transdisciplinary-specific funding is removed from a research group, center, or institution, the earlier collaborative efforts will not be sustained.[24,25] To date, this contention has not been tested directly by evaluating whether transdisciplinary teams remain productive and cohesive once their original sources of funding are expended. Nonetheless, these critiques of team science initiatives raise important questions about the continuity of collaborative research ventures once they have been initiated and funded for a determinate period (usually 3–5 years, followed by a competitive review for renewal funding).

How can a new model of transdisciplinary science funding be created that can sustain team members' efforts to develop integrative conceptual models and methodologic approaches spanning multiple fields and extended periods of collaboration (e.g., extending 10–15 years or longer)? What happens if funding of the requisite long-term support for team science initiatives is not maintained—will transdisciplinary science stagnate? Might a lack of long-term funding commitments lead researchers to revert to more traditional small,

[a]As noted by Stokols et al.[2] and Trochim et al.,[19] large-scale transdisciplinary team science includes initiatives such as those that provide \$5 million per center over the course of 5 years. These initiatives typically include 5–8 funded centers often networked through the efforts of NIH staff or a separate coordination center to facilitate cross-project and cross-center collaborations. Small-scale initiatives provide less funding and entail less formal (if any) coordination of cross-project and cross-team collaboration.

An example of a smaller-scale initiative is the Robert Wood Johnson Foundation's Active Living Research program,[20] which has accepted small-scale applications with amounts ranging from \$25,000 for 1 year to \$600,000 for 3 years. Total available award amounts ranged from \$500,000 to \$3.5 million in a given year over the first 7 years the program. Although the Active Living Research program provides some logistical support and a yearly conference to encourage knowledge sharing, these are primarily small grants being conducted by independent and dispersed transdisciplinary teams.

incremental, scientific development processes? Can substantial gains in cross-disciplinary integration and translations to health practice be achieved through small transdisciplinary science teams? Is small-scale transdisciplinary science more sustainable with respect to funding streams, or is large-scale transdisciplinary science needed to create a critical mass of researchers and infrastructure for the sustainability of transdisciplinary science? More specifically, are large, initiative-based transdisciplinary science centers needed to ensure sufficient levels of multidisciplinary expertise to propel collaborations—as well as theoretical and methodologic advances—in resolving the most urgent societal health problems? How can grant-review processes be redesigned to facilitate more rapid progress toward transdisciplinary integration and to accommodate and sustain the steadily increasing complexity of team science?[16,26] How can long-term partnerships be developed among government agencies, private industries, not-for-profit organizations, philanthropies, and foundations to ensure alternative but continuing support for cross-disciplinary team sciences?[18] What other institutional resources can be provided to encourage forward momentum and to establish long-range incentives for sustaining transdisciplinary team science?

Methods and measures to evaluate the sustainability of transdisciplinary team science are also crucial. In the context of the large transdisciplinary-center initiatives described in this supplement, evaluative strategies to assess the evidence of sustained productivity for centers that received first-round funding but were not renewed have yet to be implemented. In the context of funded research networks, advanced network analysis techniques might be considered to obtain comprehensive baseline assessments of research networks and to track these networks beyond their years of funding, assessing the degree to which a given network has retained or expanded its original set of investigators and the extent to which those investigators are representative of diverse disciplines. Moreover, assessments of a network's productivity—with respect to the extent that a network is integrative and adaptable—are likely to be critical to understanding its value-added contributions and sustainability as a team science endeavor. The evaluation of a network's productivity may include, for example, assessing the capacity of that network to successfully integrate multiple levels and diverse disciplinary knowledge to solve complex problems and to move into new areas of exploration as current problems are resolved.

In addition to resources for infrastructure and funding that stimulate and maintain team science, training is critical to the continuation of transdisciplinary team science research agendas. Without a focus on training the next generation of transdisciplinary researchers, the long-range sustainability of transdisciplinary team science is likely to be curtailed.

Training and Transformation: Developing Transdisciplinary Researchers

Transdisciplinary team science is still in the early phase of its development. Models to guide the development of transdisciplinary training curricula remain to be developed and tested. Nash[27] in this supplement summarizes various conceptual models for enhancing transdisciplinary training processes and outcomes that are associated primarily with advanced graduate student- and postdoctoral-level training. In addition to training pre- and post-doctoral scholars, providing transdisciplinary training opportunities for senior investigators is also important, as they are charged with mentoring as well as with greater management responsibilities within large research initiatives.[28,29] Broader models of transdisciplinary training that encompass the needs of all stakeholders including senior investigators, junior investigators, post-doctoral scholars, graduate students, and research support staff should be incorporated into the overall infrastructure of team science. Possible foci of these expanded transdisciplinary training programs include strategies for cultivating effective mentoring practices and leadership styles, interpersonal and managerial skills, communication strategies, technologic expertise, and coping strategies for information overload.[17]

Moreover, an important purpose of the training component of a transdisciplinary initiative is to develop the pool of emerging transdisciplinary scientists. So how are successful training processes and outcomes, and related circumstances for success, to be identified? What are the training elements that promote successful mentoring and training experiences from the perspectives of both trainees and mentors? Both retrospective and prospective evaluations of the processes and outcomes of transdisciplinary training at different stages of an initiative should be incorporated within future team science initiatives.

When considering the evaluation of transdisciplinary training, Nash[27] outlines some examples of the types of metrics and time frames that would be useful for capturing the quality, novelty, and scope of disciplinary integration of the work completed by a trainee over time. The development and application of reliable and valid metrics to assess these dimensions are sorely needed in the field. Quantitative and qualitative assessments of the career trajectories of trainees in various transdisciplinary science training programs can provide a deeper understanding of the impact of different training models and the ways in which transdisciplinary trainees gain entry to various academic, government, and private-sector positions, as well as whether their transdisciplinary training leads to sustained transdisciplinary research efforts as they move forward with their careers. For example, the assessment of trainees' evolving research orientations over time can be used to model and subsequently predict the relevant long-term career outcomes of these individuals.[12,27,28] Systematically tracking the career development trajectory of transdisciplinary trainees over time and examining the influence of earlier transdisciplinary training on their subsequent productivity will ultimately help to gauge the "returns" on team science investments at both individual and societal levels.[28]

Team Science Models and Methods

Several conceptual frameworks were presented in this supplement to describe and evaluate the processes of transdisciplinary team science.[1,12,14,21,30,31] A major focus of these models has been on understanding the factors that facilitate or constrain transdisciplinary team science collaboration. The models have been drawn from a variety of fields, such as sociology, ecology, physics, and applied mathematics. Examples of the models currently used to describe transdisciplinary team science include the social–ecologic model,[16] systems thinking and complexity theory,[18] network analysis,[27] a social-determinants paradigm,[26] and the heterarchical analytic framework.[3] These models have been used as programmatic frameworks for describing, organizing, and evaluating team science. Additionally, efforts have been focused on an integrated transdisciplinary conceptual framework for understanding and solving a problem at the early stage of team initiatives. Examples of such efforts have been documented through transdisciplinary research initiatives funded by both private and public funders.[32,33]

To date, important intellectual integration and scientific breakthroughs have been achieved within transdisciplinary team science initiatives by focusing on methodologic advances.[14] New transdisciplinary measures are showcased in the supplement.[12,14,31] With a limited number of metrics available, many authors called for new evaluative criteria to be developed—to assess, for example, recently proposed models of transdisciplinary leadership and training[27,34] and to identify valid short-term scientific outcomes.[35] Furthermore, innovative research design strategies need to be utilized and refined to overcome the remaining methodologic challenges, such as identifying appropriate comparison groups in the evaluation of transdisciplinary initiatives.[35] The creative use of existing methods should be encouraged, such as utilizing network analyses to more clearly integrate theoretical constructs of team science models and link them to relevant outcomes. Strategies such as bibliometric analysis and mapping the productivity of a transdisciplinary initiative to the overall landscape of scientific productivity of a field (e.g., tobacco-control research) are currently in progress at the NIH. Utilizing rigorous comparison-group designs, such bibliometric studies also can be used to identify similarities and differences in the quantity and quality of research productivity in both transdisciplinary science and traditional, individually-oriented research efforts. Key goals of these studies are to calibrate the potential value-added contributions of transdisciplinary science and to enable a better understanding of how supportive orientations toward transdisciplinary science (e.g., at the levels of individual investigators, research organizations, and funding agencies) influence scientific productivity and the effectiveness of health policies in the long run.

As more research in the area of interdisciplinary and transdisciplinary research and training is funded, there will be a growing need and opportunity for evaluating transdisciplinary team science. In addition to the systematic development and testing of methods and models, both infrastructure and support should be devoted to enabling such evaluations, which should include both internal and external evaluations of research programs and initiatives. The expansion of the Office of Portfolio Analysis and Strategic Initiatives at NIH continues to provide the opportunity for using internal funds to evaluate NIH-funded activities—a forward stride in building the capacity for evaluating and studying team science within the funding agency. Innovative funding mechanisms for supporting the evaluation of transdisciplinary team science collaborations should continue to be developed. Accordingly, budgetary allocations for evaluation activities are included currently in some funding mechanisms for large initiatives (e.g., the Transdisciplinary Research on Energetics and Cancer [TREC] initiative) that enables a coordination center to lead evaluation activities.[12] Separate or more clearly dedicated funding streams for transdisciplinary program evaluation, per se, would further support the design and implementation of comprehensive transdisciplinary science evaluation studies.[10,19]

Forging New Transdisciplinary Partnerships Across Sectors

An important direction for the science of team science is to examine factors that facilitate or impede productive partnerships among the multiple sectors of society that share an interest in sustaining transdisciplinary research, training, knowledge translation, and dissemination for the purpose of improving public health. As federal and state funding allocations for health research are reduced by societal demands for nonhealth-related investments (e.g., maintaining homeland security, enhancing access to higher education among low-income and minority groups), the development of creative and productive partnerships among universities, government agencies, NGOs, private foundations, and corporations aimed at cultivating and sustaining public health research will become an increasingly important task. Along those lines, a better understanding is needed of the circumstances under which public and private organizations are most likely to partner effectively to achieve shared public health goals. Gruman and Prager[36] outline examples of facilitators of effective partnerships among public research agencies (such as NIH) and philanthropic organizations (such as private health foundations); more work should be done to utilize and expand these efforts.

Also, Shen[18] in this supplement identifies conditions under which private corporations interested in commercializing health-related products might partner effectively with public funding agencies. At the same time, however, more needs to be learned about the key facilitators and constraints on effective public–private partnerships aimed at promoting improved health practices, products, and outcomes. For instance, it will be important to develop strategies for removing barriers that sometimes arise when corporate and public entities make efforts to collaborate. Examples of these barriers include scientists' concerns that their work will be distorted or tainted by market pressures as well as the profitability interests of companies contributing funding for the research, and corporate concerns that much scholarly research is impractical, unusable, and produced at a too-slow pace unsuitable for translation to commercialized health products or to improved health practices.

Conclusion

Moving Forward with Creativity

As described above, the science of team science is faced with many challenges yet to be solved. How are the value-added contributions of transdisciplinary science best assessed? When is transdisciplinary science warranted and when it is not, and how is that best decided? How can transdisciplinary science be conducted in a "smarter" manner? These questions ultimately lead to other concerns about the fundamental structure and culture in which science is conducted today and to demands for solutions that are driven by creativity. Current award mechanisms must be more creatively assessed, along with their strengths and weaknesses, with an understanding of the circumstances that indicate when an award works or does not work; new mechanisms to match current needs must be developed; more flexible infrastructures created; and a diverse array of institutionalized award mechanisms (such as the NIH P50 and U52 grants)[37] institutionalized—all of which can be used to foster the development of innovative transdisciplinary frameworks and methodologies for research development, dissemination, and practice. Examples of such initiatives, the Transdisciplinary Tobacco Use Research Centers—funded by NIH—include: the Centers for Population Health and Health Disparities, the Centers of Excellence in Cancer Communication Research, and TREC.[10,12–14] Additionally, the Clinical Translational Science Centers recently established by the National Center for Research Resources via the NIH Roadmap to promote the translation and dissemination of research findings through innovative partnerships among health scientists, practitioners, and community decision makers.[38]

The field needs to overcome the barriers between the scientific research community and the utilization-oriented private corporations to empower all stakeholders, scientists, funders, policymakers, patients, and physicians—to name but a few—in identifying urgent problems and setting research agendas and priorities for the ultimate benefit of the nation.[18,36] Also needed is a culture that promotes appreciation and recognition of team science and that rewards team effort and contributions, nurturing a value system that encourages equitable research arrangements and collective leadership/authorship models.[34,39] Further, the scientific community can contribute to an appreciation of team effort and team contributions by creating new cross-disciplinary journals and new criteria for tenure and promotion. Also to be engaged are higher education accreditation organizations, journal editors, review boards, funding agencies, scientists, university presidents, and deans in promoting and sustaining innovative and collaborative partnerships among health scientists, community practitioners, and policymakers.

As an increasing amount of funding has been allocated for transdisciplinary team science, especially during times of constrained budgets, critics have argued that transdisciplinary initiatives take precious resources away from more productive sole-investigator (and typically unidisciplinary) work.[17,24,25] Systematic and rigorous studies of the scientific and societal health impacts of different funding mechanisms are warranted for the next steps of team science development. The science of team science can be advanced through systematic assessments and a strong research agenda. But, more importantly, a creative approach is needed to cultivate a broader culture of integrated, heterarchical scientific inquiry.[30] Boundaries must be pushed not only by the development of new scientific models, methods, and measures, but also by the initiation of organizational innovations that create fundamental changes in the ways scientists do business—changes that embrace multiple disciplines, sectors, and cultures; revolutionize award mechanisms, funding streams, and publications; and allow flexibility and fluidity to eliminate the constraints of rigid hierarchic structures[30]—to release talent bound by towers of tradition into a sea of creativity. A new era of creativity and innovation in transdisciplinary science can be achieved through simultaneous and coordinated efforts that remove collaborative barriers and build new linkages across multiple sectors of society and across spheres of research. In this new era of creativity and innovation in transdisciplinary research, current scientific research paradigms and infrastructures will be transformed in ways that enable the world's scientists to leverage global resources to resolve the most pressing environmental and public health problems of the 21st Century.

No financial disclosures were reported by the authors of this paper.

References

1. Klein JT. Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 2008;35(2S):S116–S123.
2. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 2008;35(2S):S77–S89.
3. National Cancer Institute. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13474; videocast.nih.gov/Summary.asp?File=13471.
4. Kessel FS, Rosenfield PL, Anderson NB, eds. Interdisciplinary research: case studies from health and social science. New York: Oxford University Press, 2008.
5. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.
6. Farber G. An overview of the NIH Roadmap initiative. Proceedings of the NCI–NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13474.
7. NIH. NIH Roadmap for medical research: interdisciplinary research. 2003. nihroadmap.nih.gov/interdisciplinary/index.asp.
8. Stokols D. Toward a science of transdisciplinary action research. Am J Community Psychol 2006;38:63–77.
9. Aronoff NL, Bailey D. Social work practice guidelines in an interprofessional world: honoring new ties that bind. In: Rosen AK, Proctor EK, eds. Developing practice guidelines for social work interventions. New York: Columbia University Press, 2003.
10. Croyle RT. The National Cancer Institute's transdisciplinary centers initiatives and the need for building a science of team science. Am J Prev Med 2008;35(2S):S90–S93.
11. Hays TC. The science of team science: commentary on measurements of scientific readiness. Am J Prev Med 2008;35(2S):S193–S195.
12. Hall KL, Stokols D, Moser RP, et al. The collaboration readiness of transdisciplinary research teams and centers: findings from the National Cancer Institute's TREC year-one evaluation study. Am J Prev Med 2008;35(2S):S161–S172.
13. Holmes JH, Lehman A, Hade E, et al. Challenges for multilevel health disparities research in a transdisciplinary environment. Am J Prev Med 2008:35(2S):S182–S192.
14. Mâsse LC, Moser RP, Stokols D, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med 2008; 35(2S):S151–S160.
15. Sallis J, Oberholtzer C, Mitrany M. Lessons learned-developing new strategies for strengthening transdisciplinary science and training initiatives. Proceedings of the NCI-NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30-31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13471.
16. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. Am J Prev Med 2005;28(2S2):202–13.
17. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. Am J Prev Med 2008;35(2S):S96–S115.
18. Shen B. Toward cross-sectoral team science. Am J Prev Med 2008; 35(2S):S240–S242.
19. Trochim WM, Marcus SE, Mâsse LC, Moser RP, Weld PC. The evaluation of large research initiatives: a participatory integrated mixed-methods approach. Am J Eval 2008;29:8–28.
20. Robert Wood Johnson Foundation. Active living research. 2008. www.activelivingresearch.org/.
21. Leischow SJ, Best A, Trochim WM, et al. Systems thinking to improve the public's health. Am J Prev Med 2008;35(2S):S196–S203.
22. Hesse BW. Of mice and mentors: developing cyber-infrastructure to support transdisciplinary scientific collaboration. Am J Prev Med 2008; 35(2S):S235–S239.
23. Syme SL. The science of team science: assessing the value of transdisciplinary research. Am J Prev Med 2008;35(2S):S94–S95.
24. Marks AR. Rescuing the NIH before it is too late. J Clin Invest 2006; 116:844.
25. Weissmann G. Roadmaps, translational research, and childish curiosity. FASEB J 2005;19:1761–2.
26. Morgan G, Kobus K, Gerlach KK, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine Tob Res 2003;5(1S):S11–S19.
27. Nash JM. Transdisciplinary training: key components and prerequisites for success. Am J Prev Med 2008;35(2S):S133–S140.
28. Mitrany M, Stokols D. Gauging the transdisciplinary qualities and outcomes of doctoral training programs. J Plann Educ Res 2005;24:437–49.
29. Rhoten D, Parker A. Education: risks and rewards of an interdisciplinary research path. Science 2004;306:2046.
30. Kessel FS, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. Am J Prev Med 2008;35(2S):S225–S234.
31. Provan KG, Clark P, Huerta T. Transdisciplinarity among tobacco harm–reduction researchers: a network analytic approach. Am J Prev Med 2008;35(2S):S173–S181.
32. Clayton RR, Merikangas KR, Abrams DB. Tobacco etiology research network (TERN) grant results. 2000. www.rwjf.org/programareas/resources/grantsreport.jsp?filename=tern.htm&pid=1141&gsa=5.
33. Kahn RL. An experiment in scientific organization. Chicago IL: The John D. and Catherine T. MacArthur Foundation, Program in Mental Health and Human Development. A MacArthur Foundation Occasional Paper; 1993. http://www.macfound.org/atf/cf/%7BB0386CE3-8B29-4162-8098-E466FB856794%7D/experiment_in_scientific_organization.pdf.
34. Gray B. Enhancing transdisciplinary research through collaborative leadership. Am J Prev Med 2008;35(2S):S124–S132.
35. Moser RP, Gladden M, Ames M, Porter D, Marcus S. Reflections on new concepts and methods for evaluating transdisciplinary research and training. Proceedings of the NCI-NIH Conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research. 2006 Oct 30–31; Bethesda MD. videocast.nih.gov/Summary.asp?File=13471.
36. Gruman J, Prager D. Health research philanthropy in a time of plenty: a strategic agenda. Health Aff 2002;21:265–9.
37. NIH. Types of grant programs. 2008. grants.nih.gov/grants/funding/funding_program.htm.
38. National Center for Research Resources. Clinical and translational science awards to transform clinical research. 2006. www.ncrr.nih.gov/ncrrprog/roadmap/CTSA_9-2006.asp.
39. Altman DG. Sustaining interventions in community systems: on the relationship between researchers and communities. Health Psych 1995; 14:526–36.

Author Index

Subject Index

 0749-3797/08/$–see front matter

U

W

Y